TEM, LEAP, and Interfacial Defects of AlGaN/GaN HEMTs

Ray Holzworth, Patrick Whiting,

Nicholas Rudawski, and Kevin Jones

Department of Materials Science & Engineering

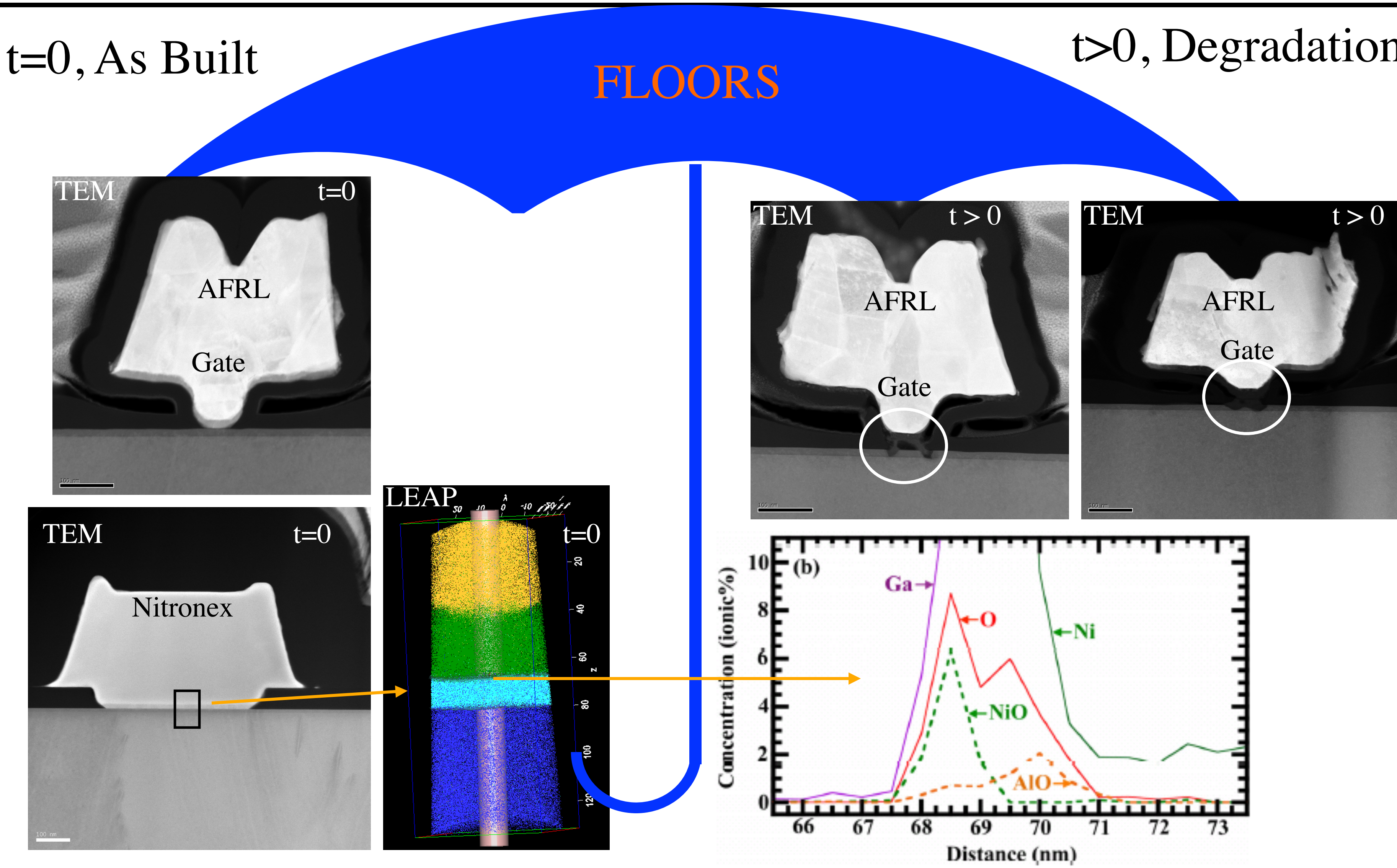
Lu Liu, Tsung-Sheng Kang, and Fan Ren

Department of Chemical Engineering

Gator Engineering

University of Florida

TEM, LEAP, and Interfacial Defects of AlGaN/GaN HEMTs

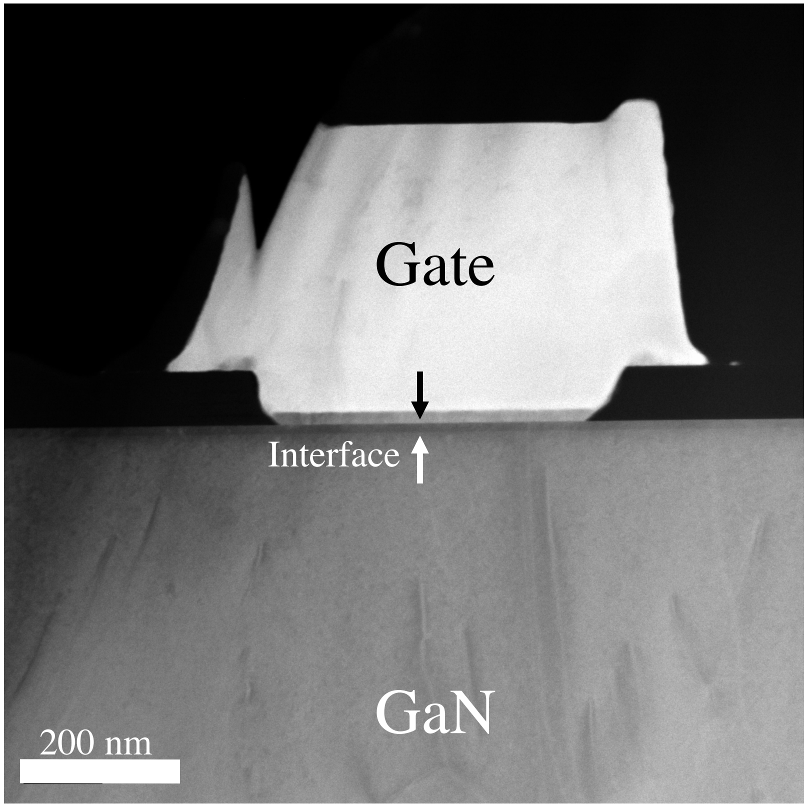


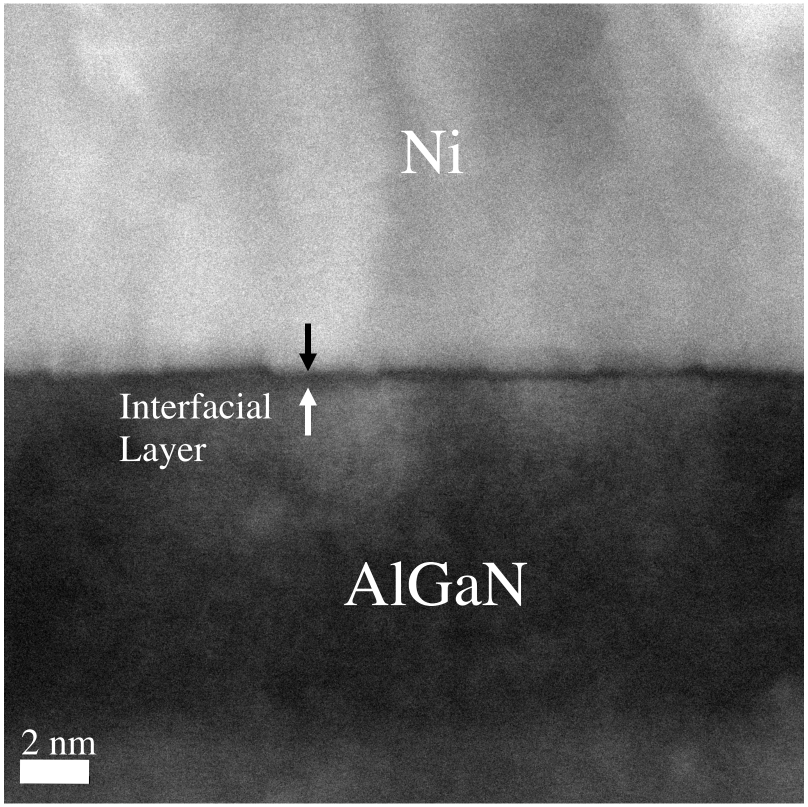
Outline

- Devices Analyzed
  - Nitronex (Ni-gate) (t = 0)
    - TEM
      - Interfaces
    - LEAP
      - Review
      - Data Reanalysis → Improved Results
  - MIT (TriQuint) (Pt-gate) (t > 0)
    - Update on Collaboration
    - TEM
      - Interfaces and Defects
    - LEAP
      - Angled tip and results
  - AFRL (Ni-gate) (t = 0 and t > 0)
    - TEM
      - Interfacial defects
    - LEAP
- Limitations of LEAP
- Current Collaborations
- Conclusions
- Future Work

TEM of Nitronex Gate/Epi Interface

- TEM (STEM-HAADF)
  - t = 0





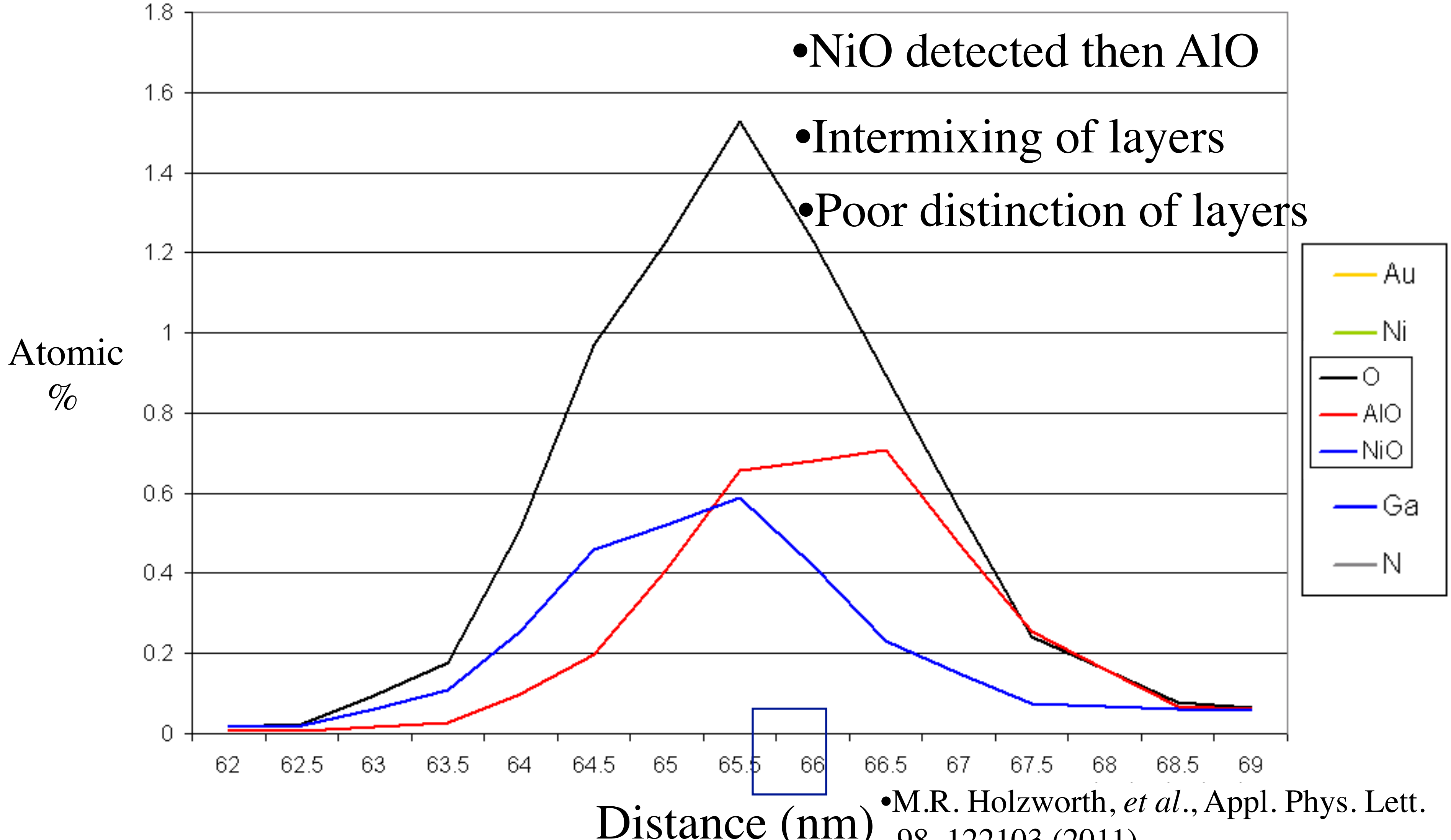
- Interfacial layer is ~5Å
- Composed of NiO_x and AlO_x (LEAP)

Last Review: 1-D Concentration Profile (Nitronex)

•NiO detected then AlO

•Intermixing of layers

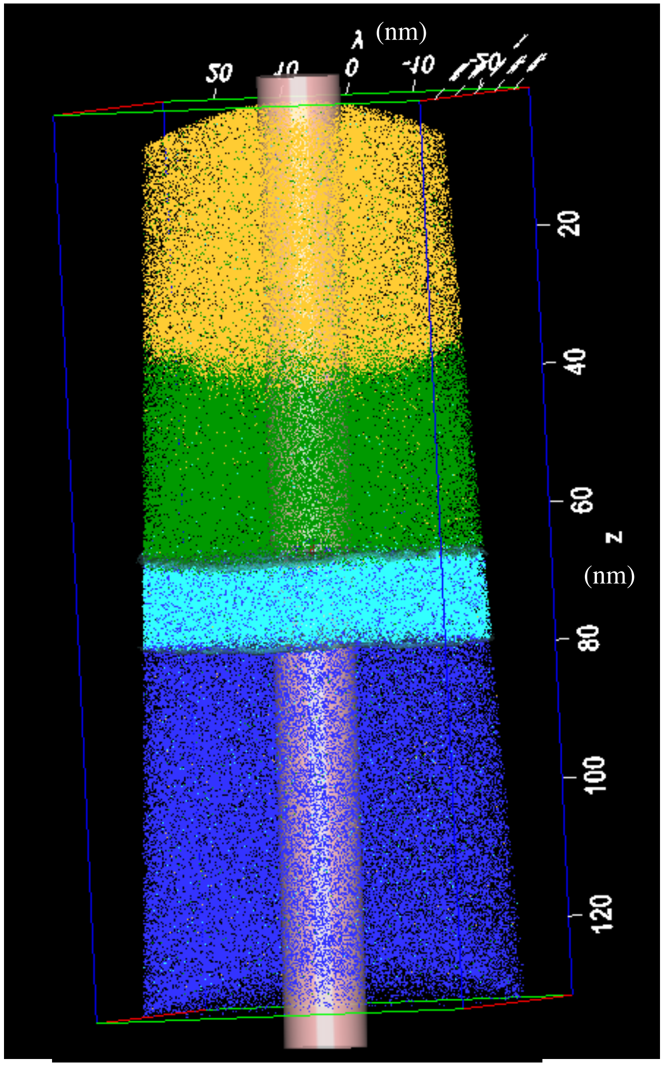
•Poor distinction of layers



•M.R. Holzworth, *et al*., Appl. Phys. Lett. 98, 122103 (2011).

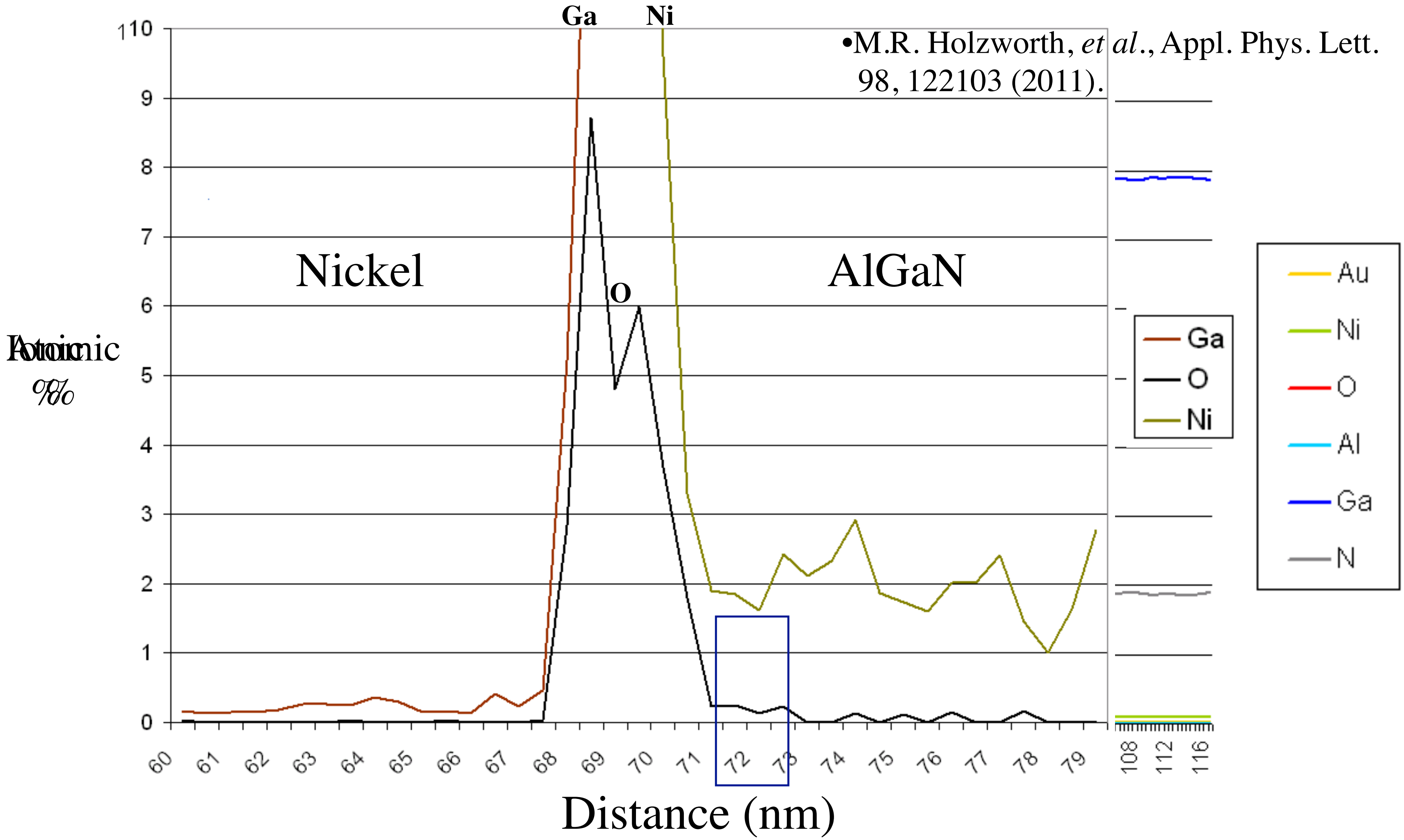
How is Data Reanalyzed for Greater Accuracy?

- Find the iso-surface
- Position data pipe relative to iso-surface of interest
- Use data pipe to collect information
  - Analysis occurs along the length of the pipe and across the cross sectional area

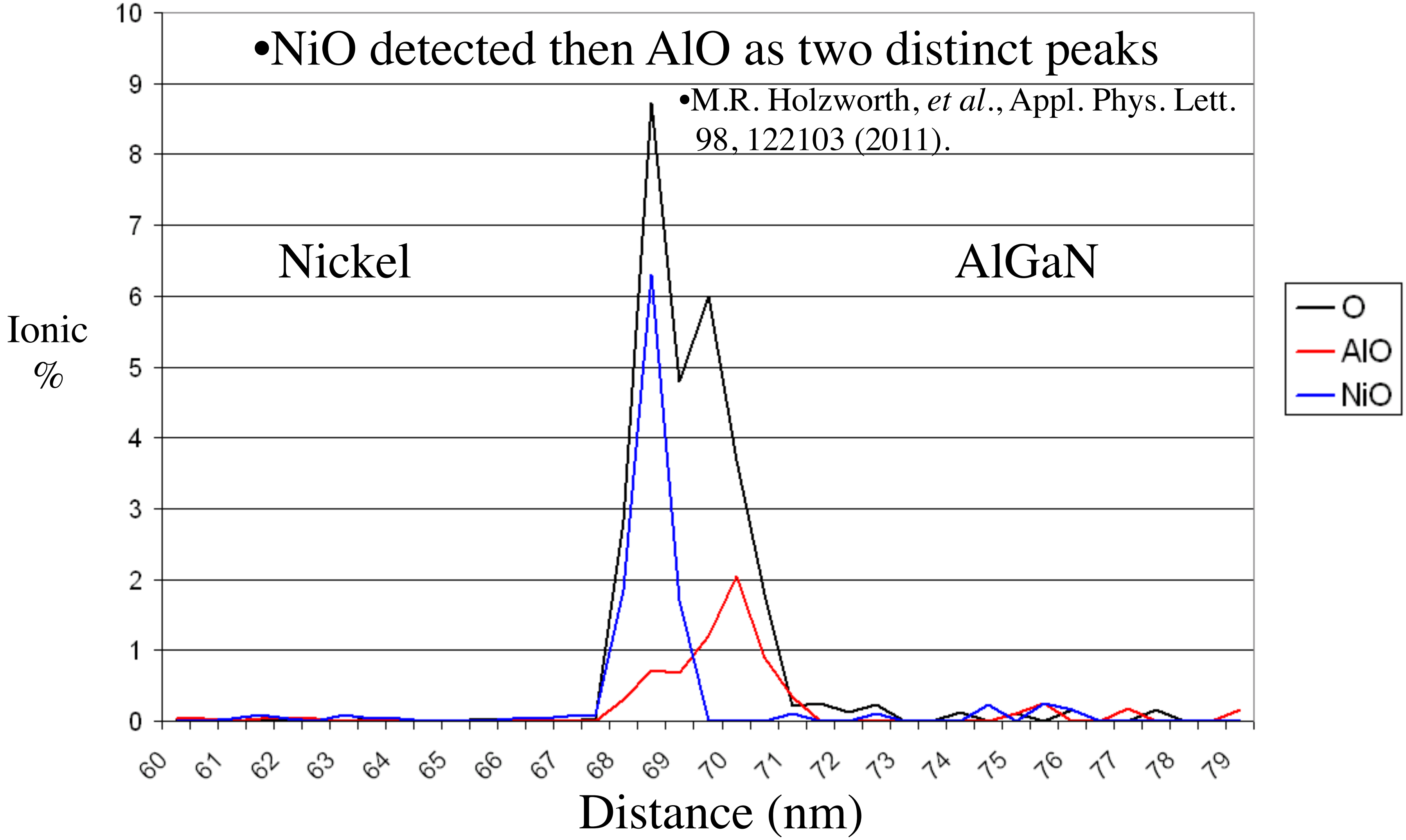


Closer Inspection of the 1-D Concentration Profile (Nitronex)

•M.R. Holzworth, *et al*., Appl. Phys. Lett. 98, 122103 (2011).

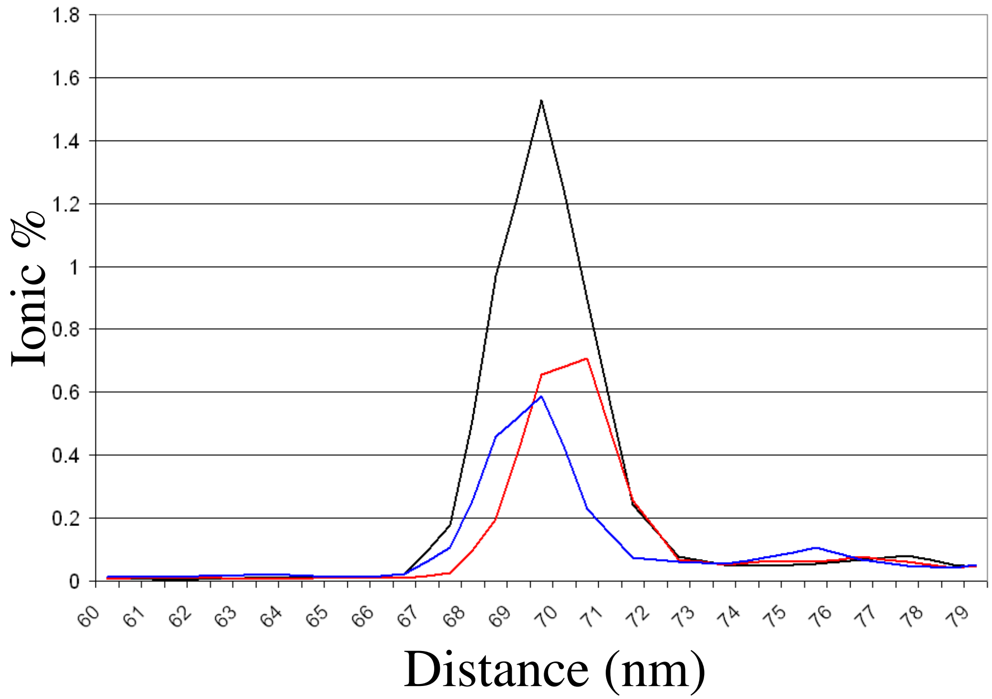


Closer Inspection of the 1-D Concentration Profile (Nitronex)

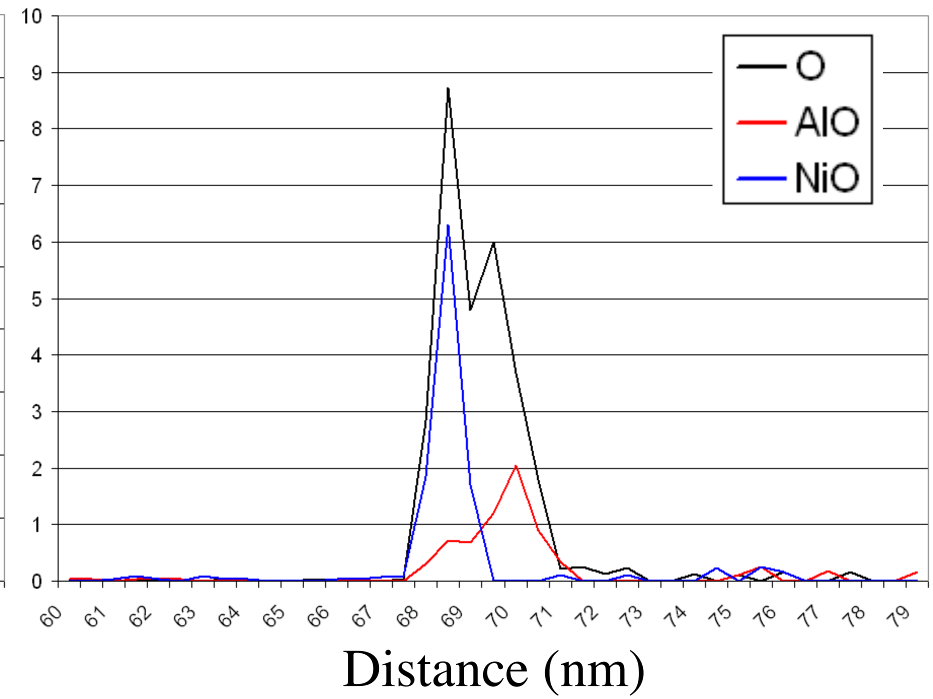


Comparison between 1-D Profiles (Nitronex)

- Before



- After



- Improved interface resolution
  - Layer abruptness increased (6 nm vs 3.5 nm)
  - Layer mixing is decreased (distinct oxide layers)

Outline

- Devices Analyzed
  - Nitronex (Ni-gate) (t = 0)
    - TEM
      - Interfaces
    - LEAP
      - Review
      - Data Reanalysis → Improved Results
  - MIT (TriQuint) (Pt-gate) (t > 0)
    - Update on Collaboration
    - TEM
      - Interfaces and Defects
    - LEAP
      - Angled tip and results
  - AFRL (Ni-gate) (t = 0 and t > 0)
    - TEM
      - Interfacial defects
    - LEAP
- Limitations of LEAP
- Current Collaborations
- Conclusions
- Future Work

Update on MIT Collaboration

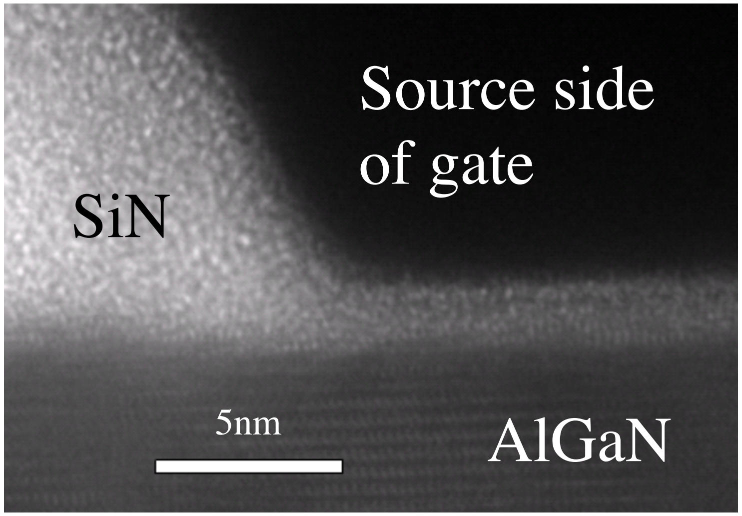
- Collaboration
  - Prof. Jesus del Alamo at MIT
  - Group suggested the inverse piezoelectric effect for failure and have done the initial work in the area
  - TriQuint Devices

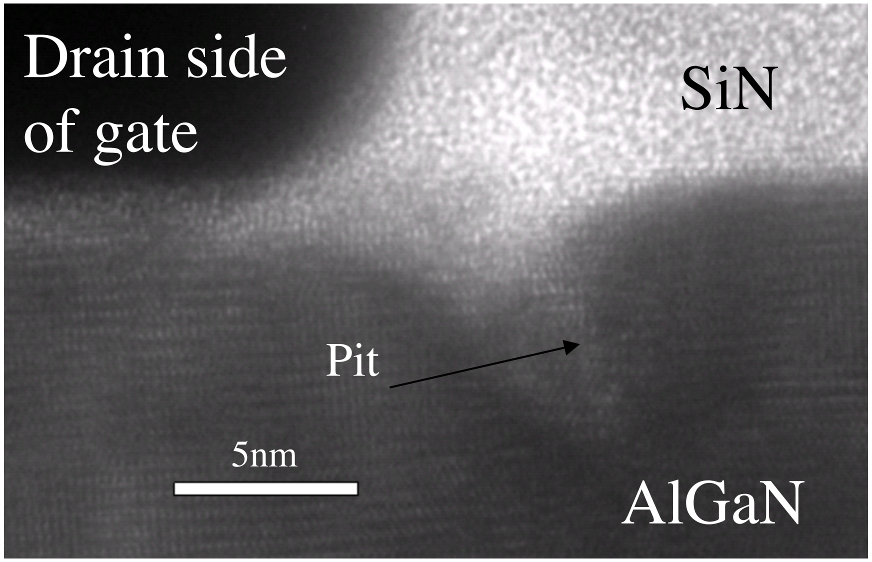
- They provide us with unstressed and stressed fingers on a device

- We provide:
  - TEM
    - Image defects (non-uniform along gate width)
  - LEAP
    - Determine the composition of the pit and crack defects
      - Knowing composition would help formulate formation mechanisms for defects

Update on MIT Collaboration

- TEM
  - Pt-gate
  - t > 0

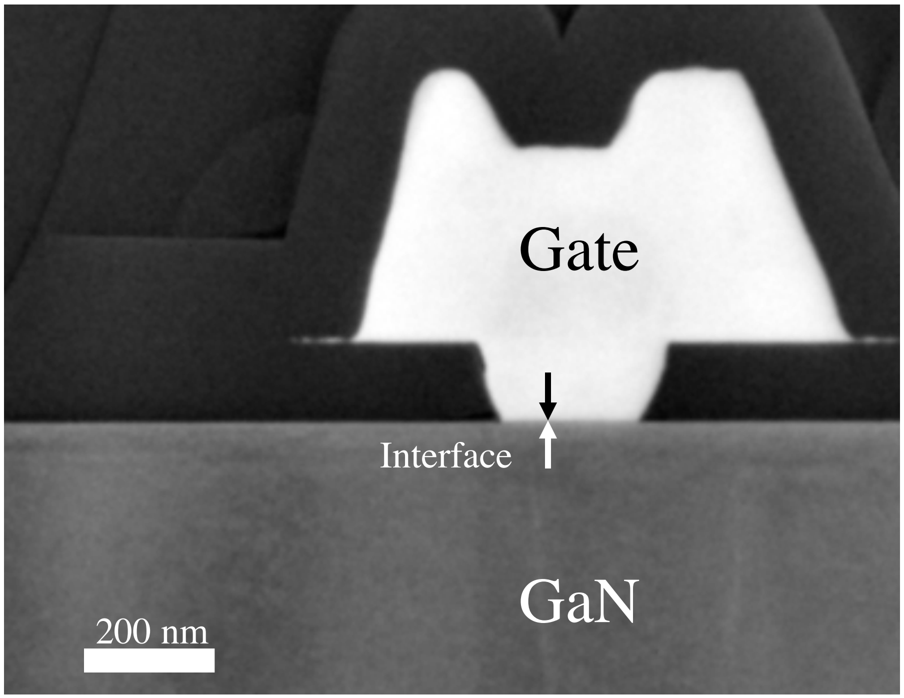


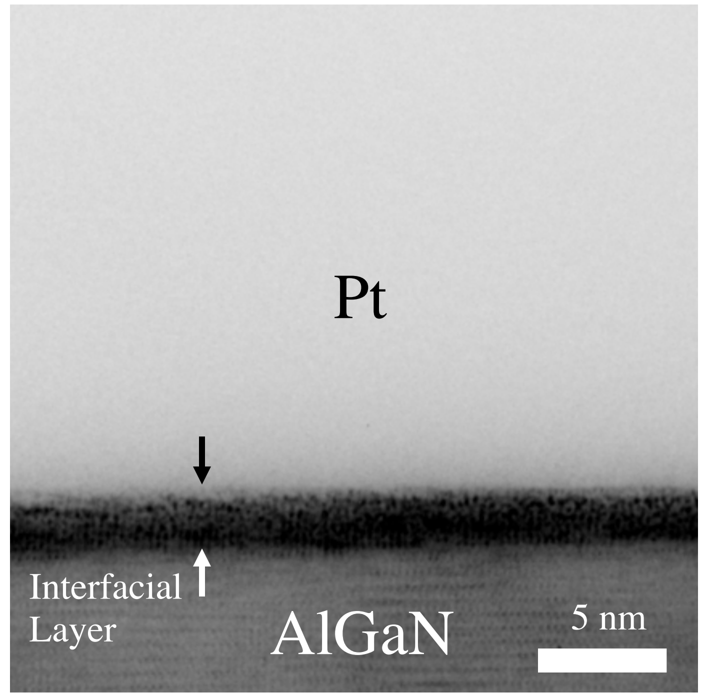


Sample courtesy of
Jesus del Alamo and Jungwoo Joh

TEM of MIT (TriQuint) Gate/Epi Interface

- TEM
  - Pt-gate
  - t > 0

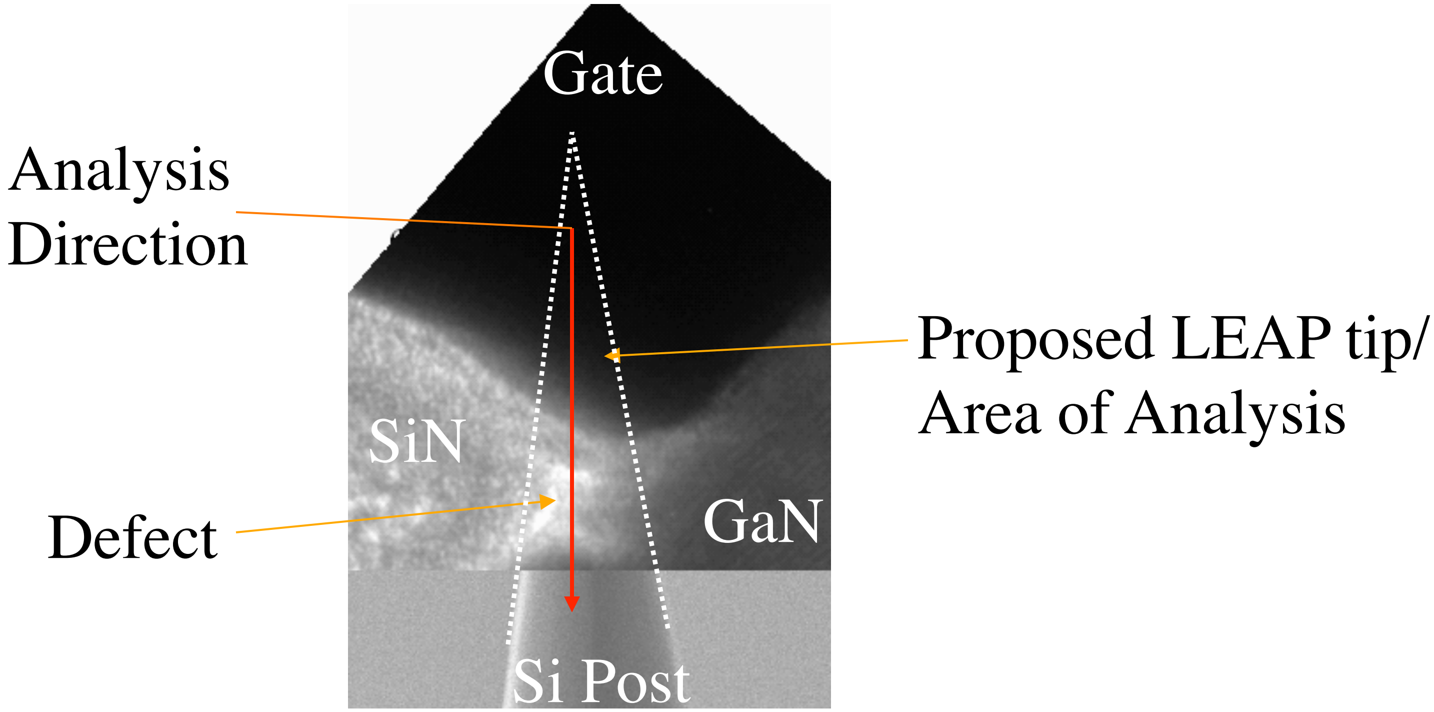




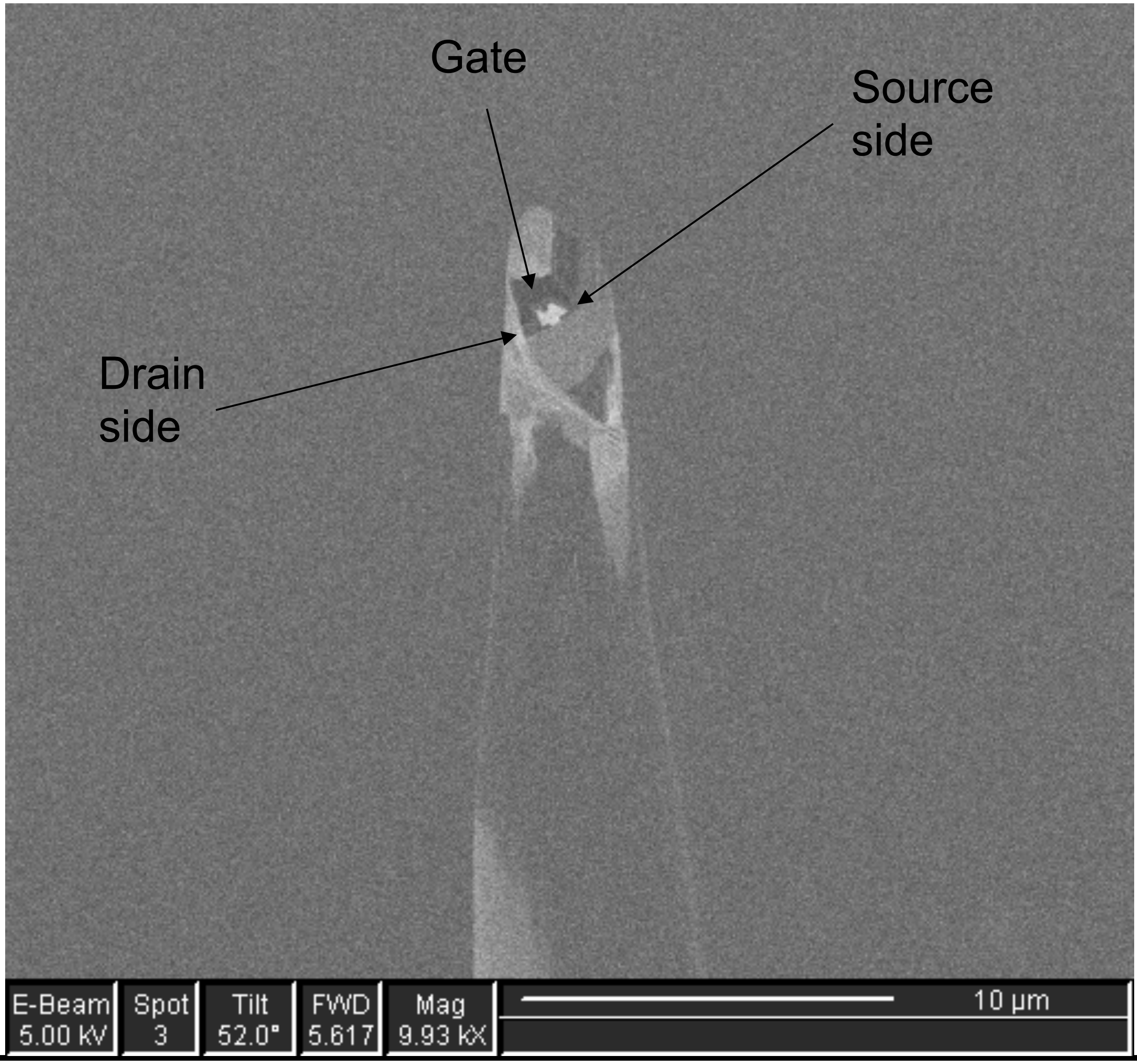
- Interfacial layer is ~18Å
- Unknown composition

Proposed Schematic of MIT LEAP Tip

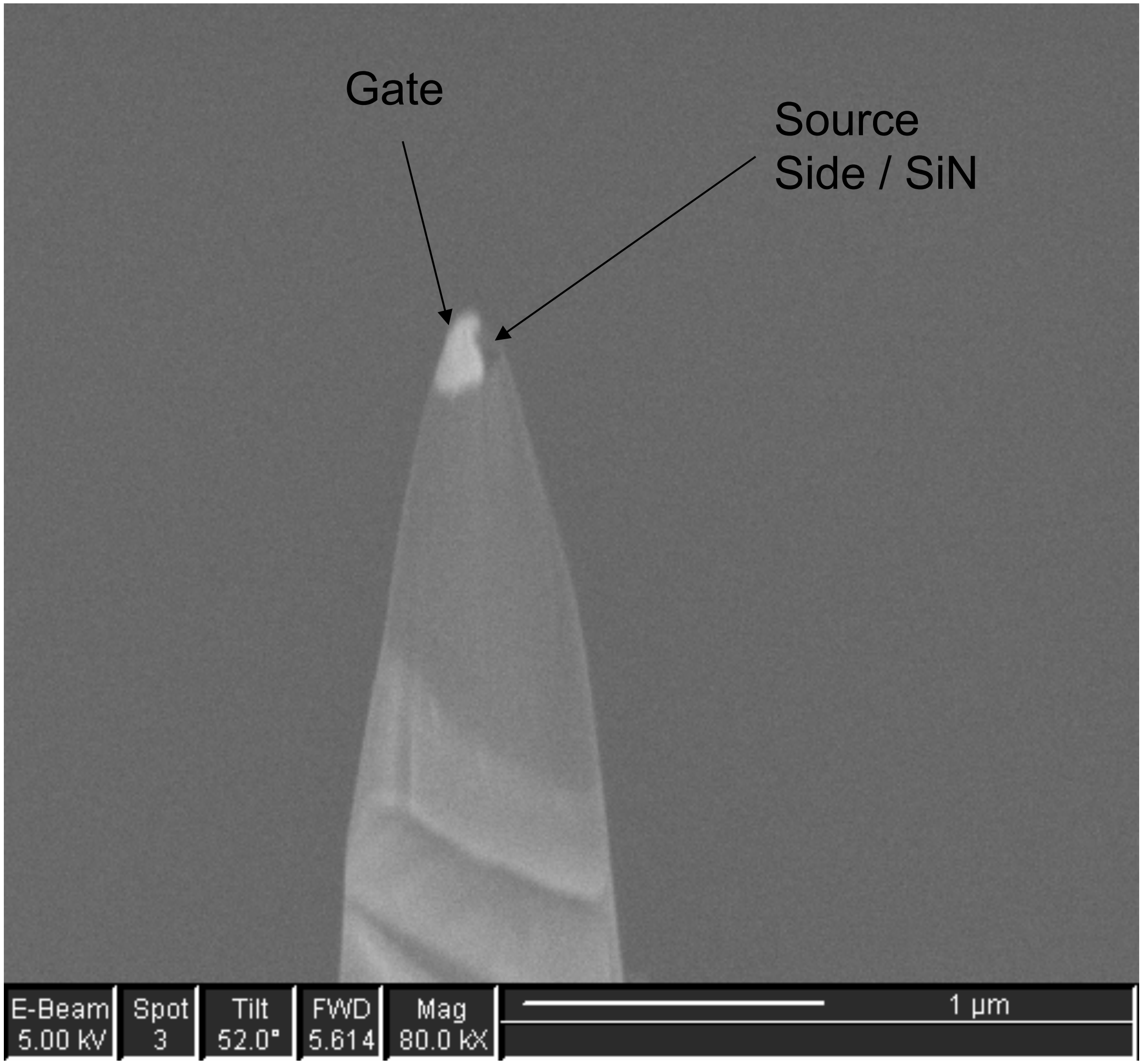
- LEAP
  - Perform LEAP analysis through the defect to determine the composition
    - Device will be mounted at an angle
    - Analysis will start in the gate metal then transition into defect



Layout of LEAP Tip

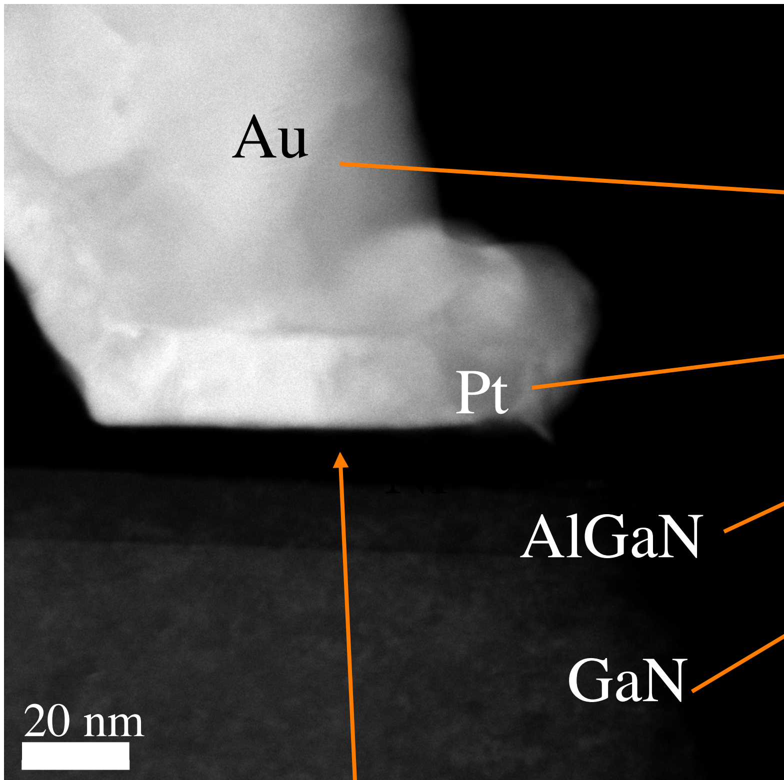


Layout of LEAP Tip



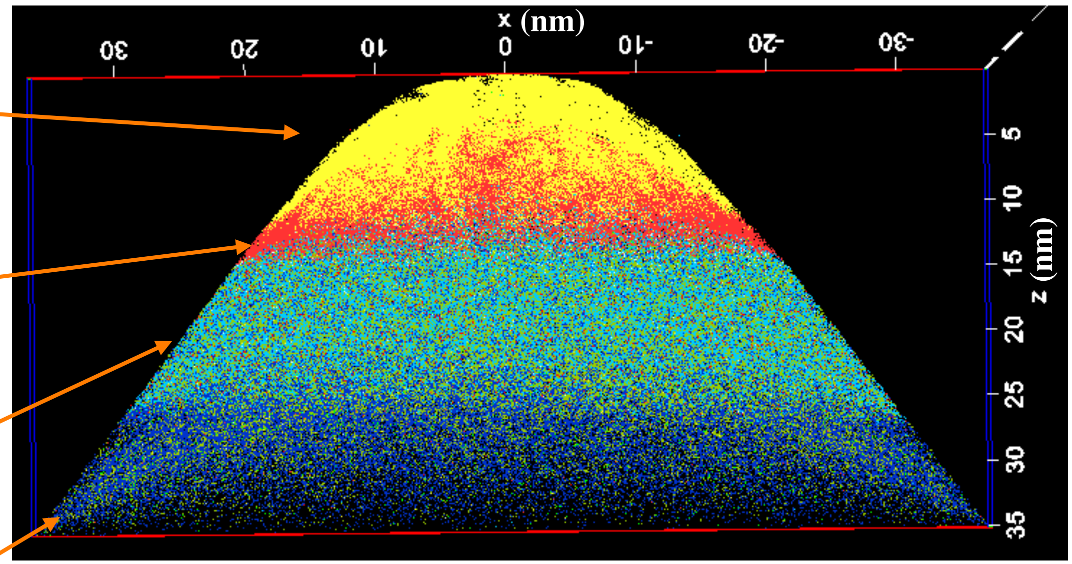
LEAP from MIT Collaboration

- TEM (STEM-HAADF)
  - Pt-gate
  - t > 0



- Delamination from fib milling; not the size of the interfacial layer

- LEAP



- Reconstruction flawed due to tip fracture/ delamination
- Pt and AlGaN layers are thin and interfaces have poor shape

Update on MIT Collaboration

- MIT (TriQuint) devices fracture at interfaces using LEAP
  - Thick interfacial layer between the gate and epi-layers attributes to LEAP tip fracture and delamination
  - Inhibits acquisition of composition of pit defect near interface
  - Using a different LEAP or atom probe system with a smaller laser wavelength may correct this issue
- TriQuint has no further interest in this collaboration

Outline

- Devices Analyzed
  - Nitronex (Ni-gate) (t = 0)
    - TEM
      - Interfaces
    - LEAP
      - Review
      - Data Reanalysis → Improved Results
  - MIT (TriQuint) (Pt-gate) (t > 0)
    - Update on Collaboration
    - TEM
      - Interfaces and Defects
    - LEAP
      - Angled tip and results
  - AFRL (Ni-gate) (t = 0 and t > 0)
    - TEM
      - Interfacial defects
    - LEAP
- Limitations of LEAP
- Current Collaborations
- Conclusions
- Future Work

Defects Overview

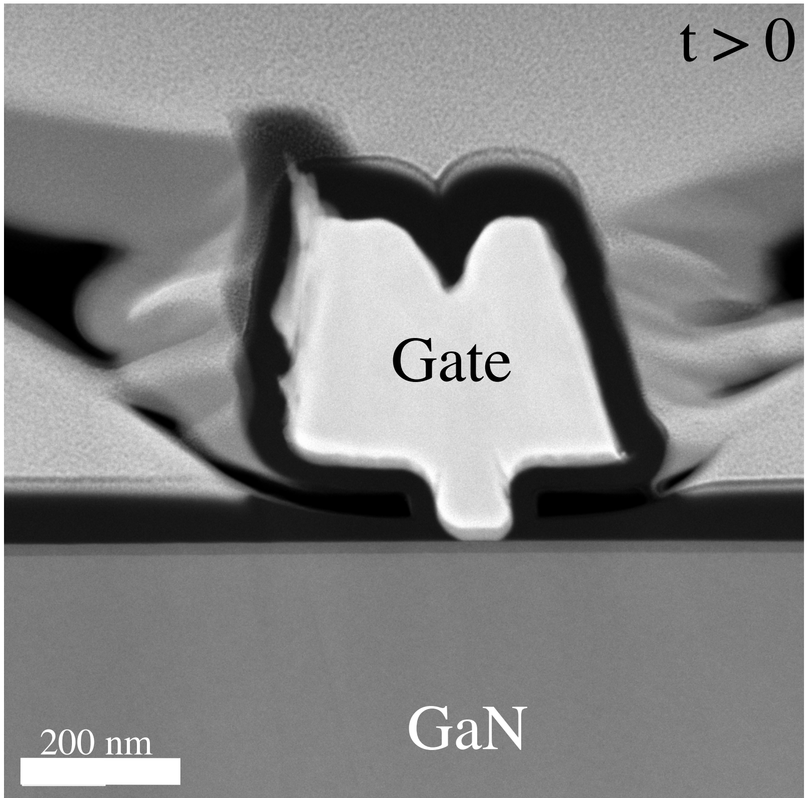
- Observe defects from different stress conditions
- Characterize defects:
  - Chemical
  - Structural

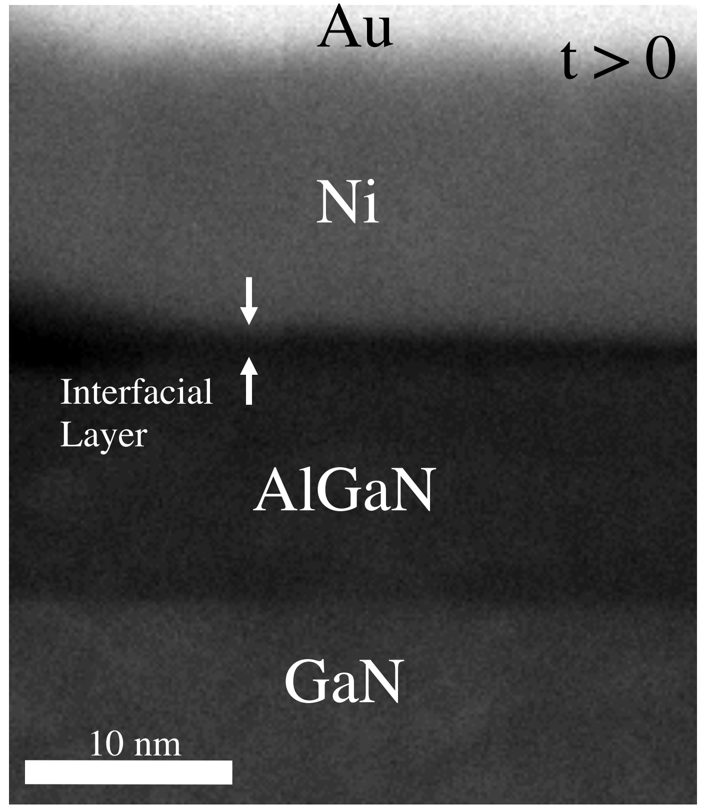
  Using:
  - TEM
    - EDS
  - Atom Probe

To determine possible failure mechanisms:
- Improve reliability
- Improve modeling

TEM of AFRL Gate/Epi Interface

- TEM (STEM-HAADF)
  - Ni-gate

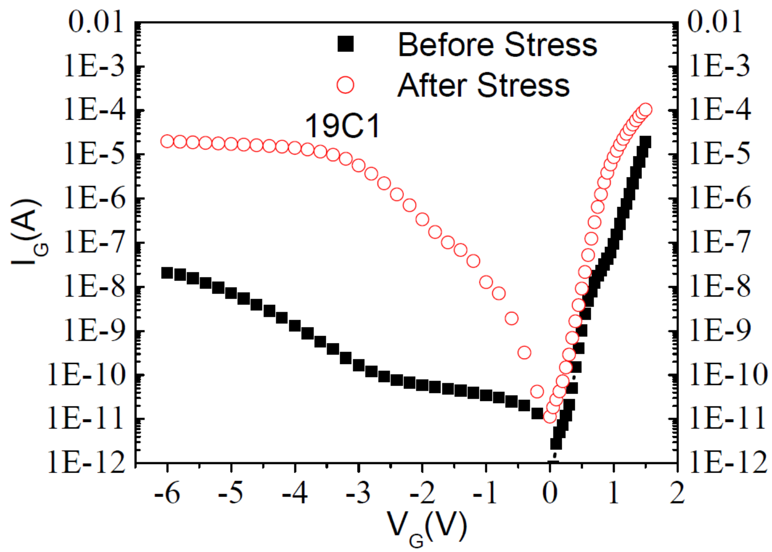




- Interfacial layer is ~15Å
- Unknown composition

AFRL Device 1514

- Device History
  - Made by: AFRL
  - Electrically stressed by: Dr. Ren's Group



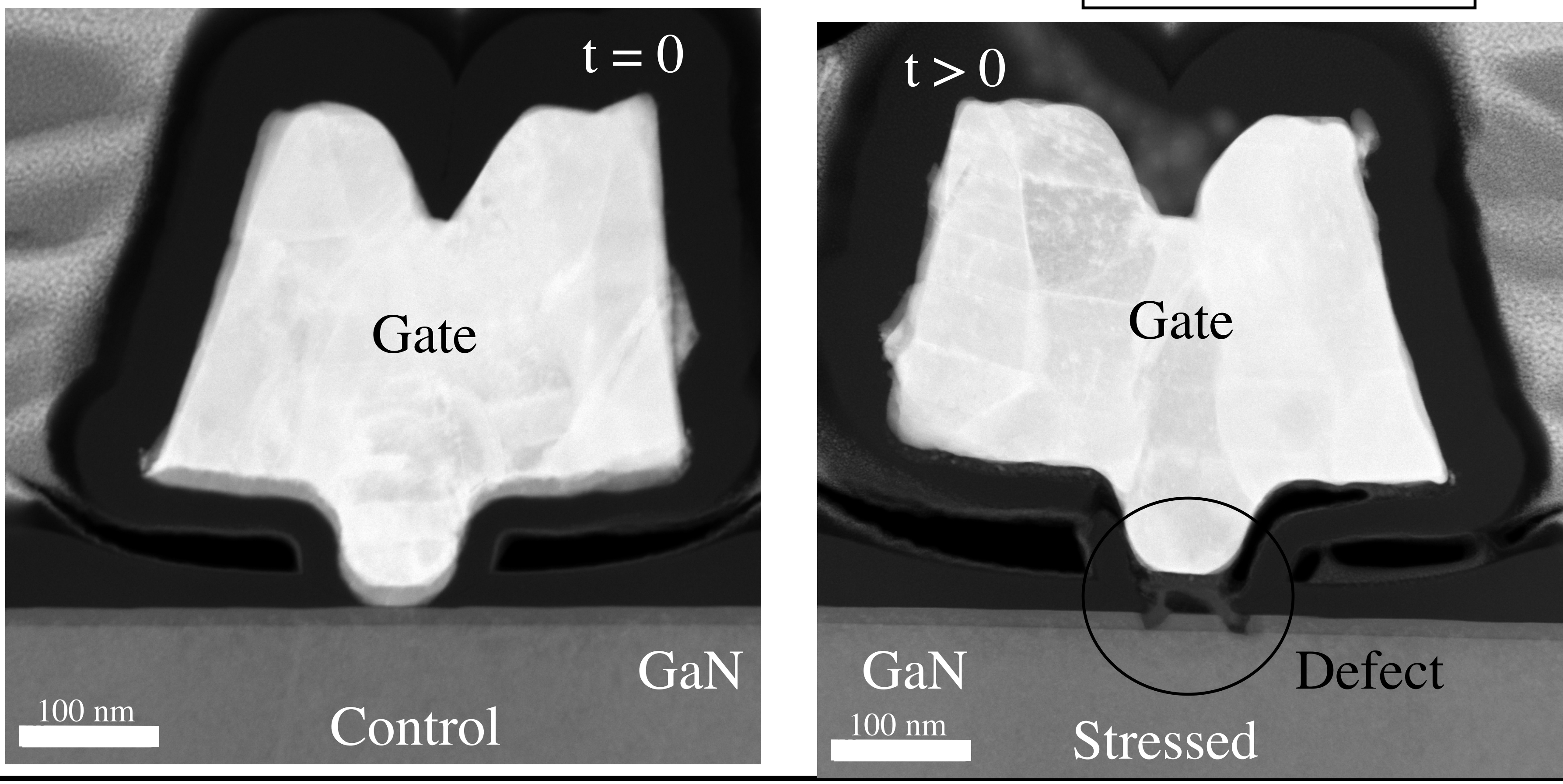
  - TEM analysis by: Dr. Jones's Group

AFRL Device 1514

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate

Stress Conditions

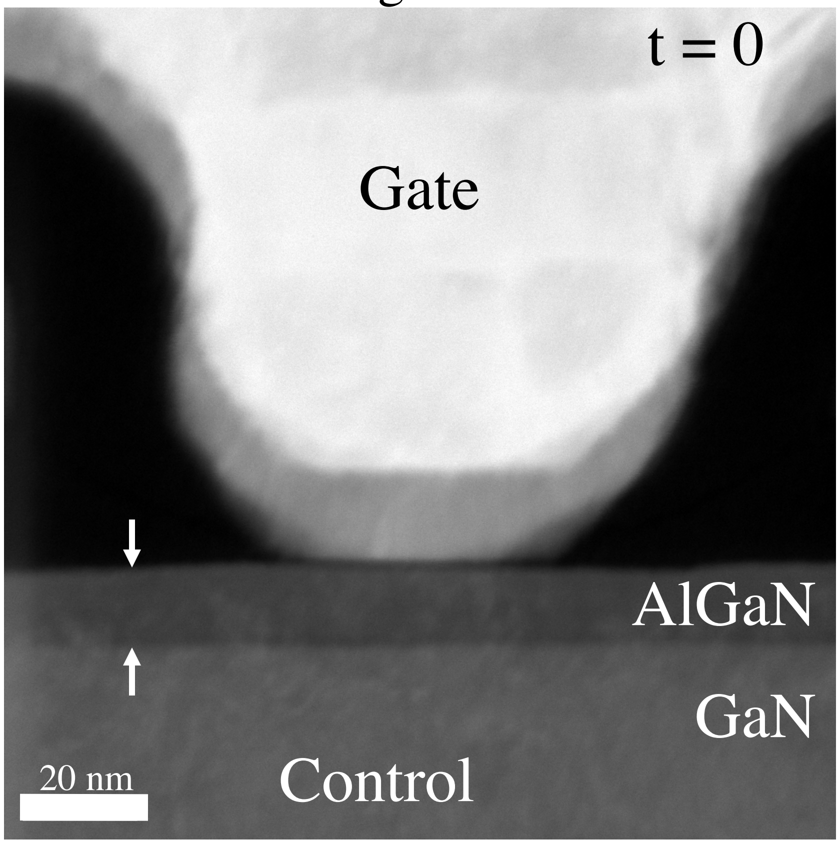
V_{DS} = 5V
V_G = -5V to -42V
•1 min steps

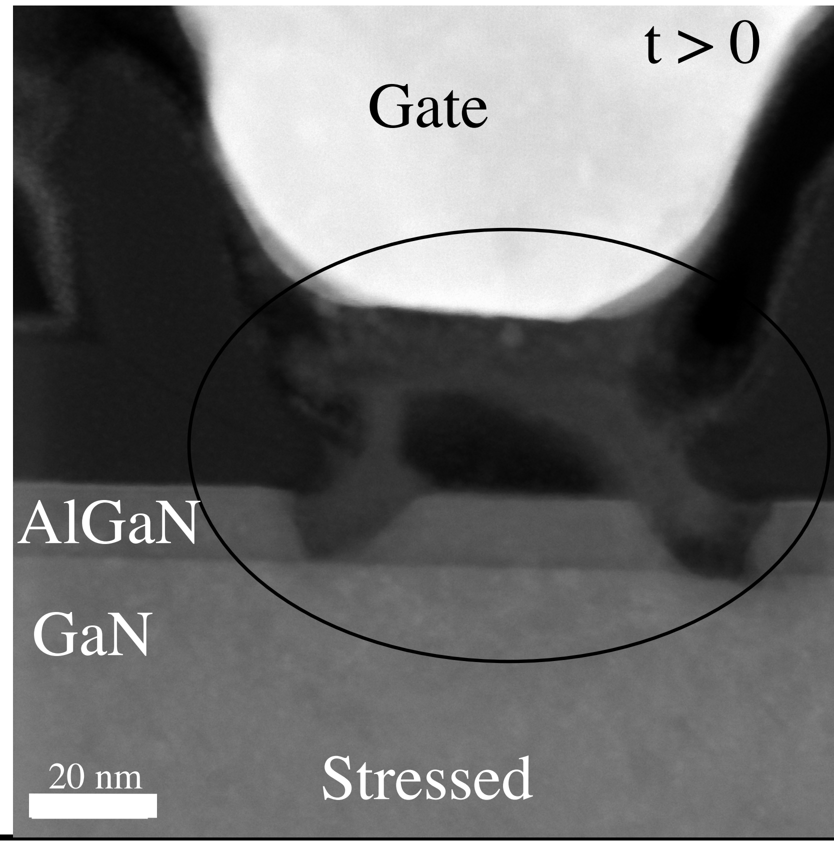


AFRL Device 1514

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate

Stress Conditions
V_{DS} = 5V
V_G = -5V to -42V
•1 min steps

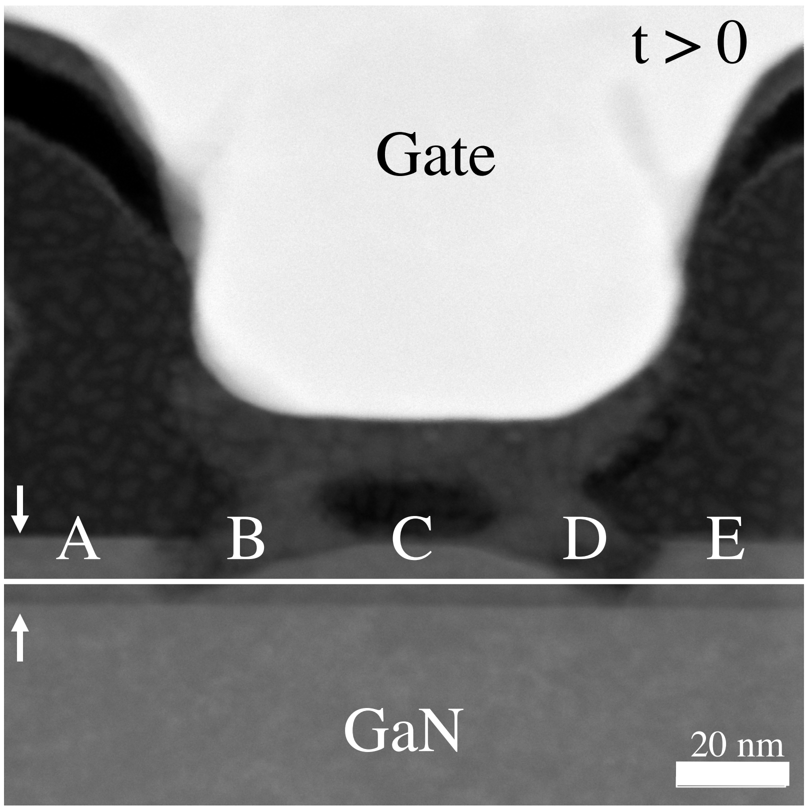


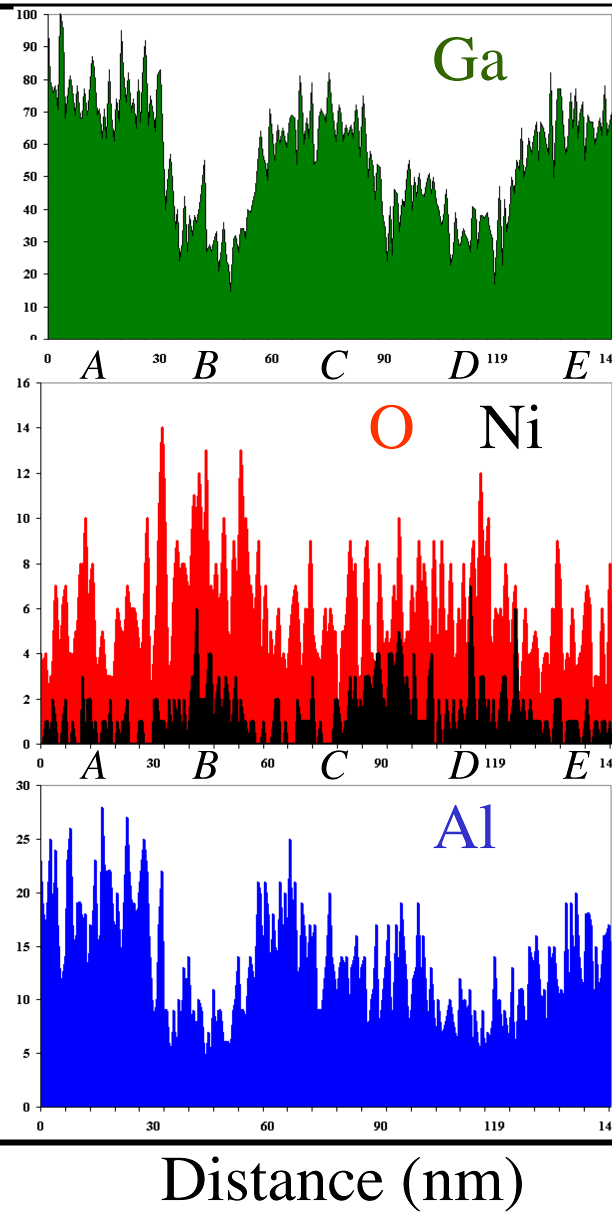


•Defect present

EDS Line Scan across AlGaN Layer of 1514

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate





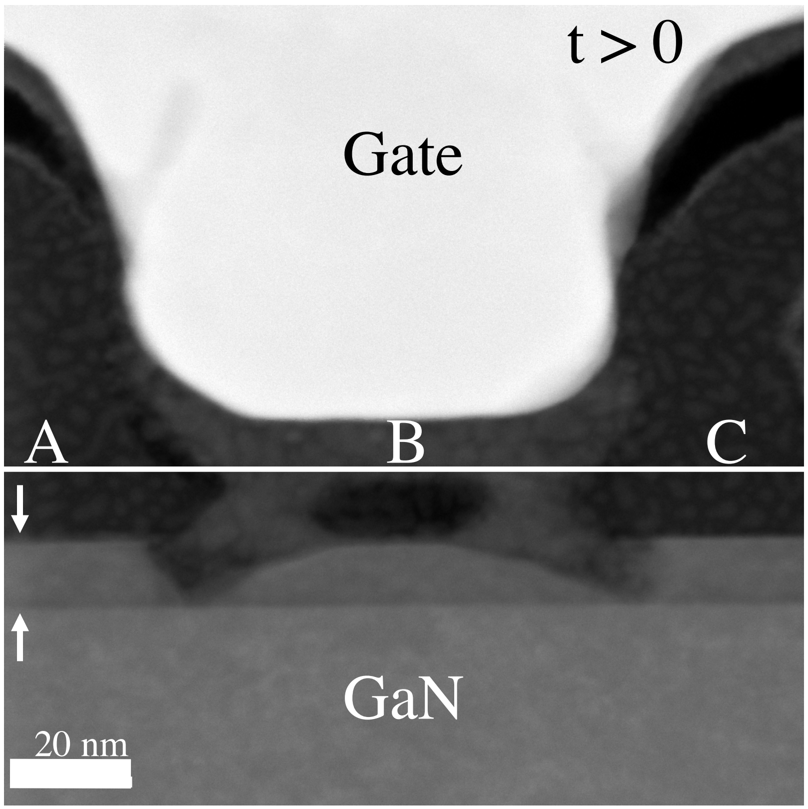
•Ga decreases in the arch feet

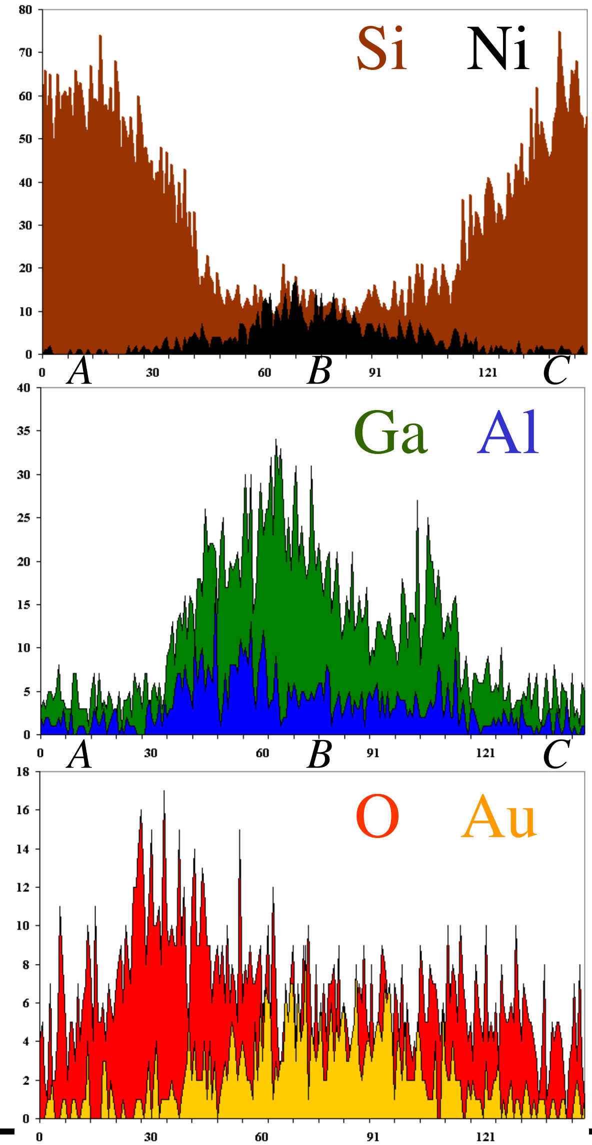
•Ni and O increase in the arch feet

•Al decreases in the arch feet

EDS Line Scan across Defect of 1514

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate





Distance (nm)

- Ni detected in the defect
- Ga and Al increase in the defect
- O and Au increase in the defect

AFRL Device 1514 Conclusions

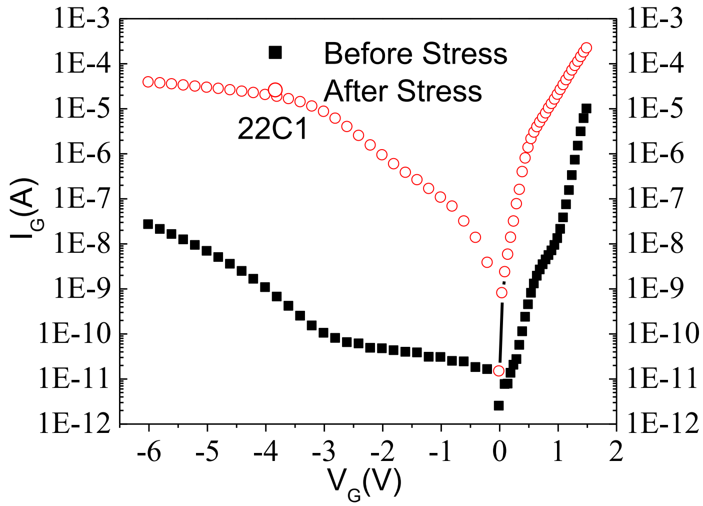
- Small defect present under 100nm gate

- Found completely throughout the gate width
  - Defect in every TEM and SEM slice
    - Approximately 15 slices

- Defect appears to have different compositions in the Nickel gate region and the AlGaN region
  - AlGaN: Increase in O and Ni
    Decrease in Ga and Al
  - Ni: Increase in Au, Ga, Al, and O
    None to little Si

AFRL Device 1813

- Device History
  - Made by: AFRL
  - Electrically stressed by: Dr. Ren's Group

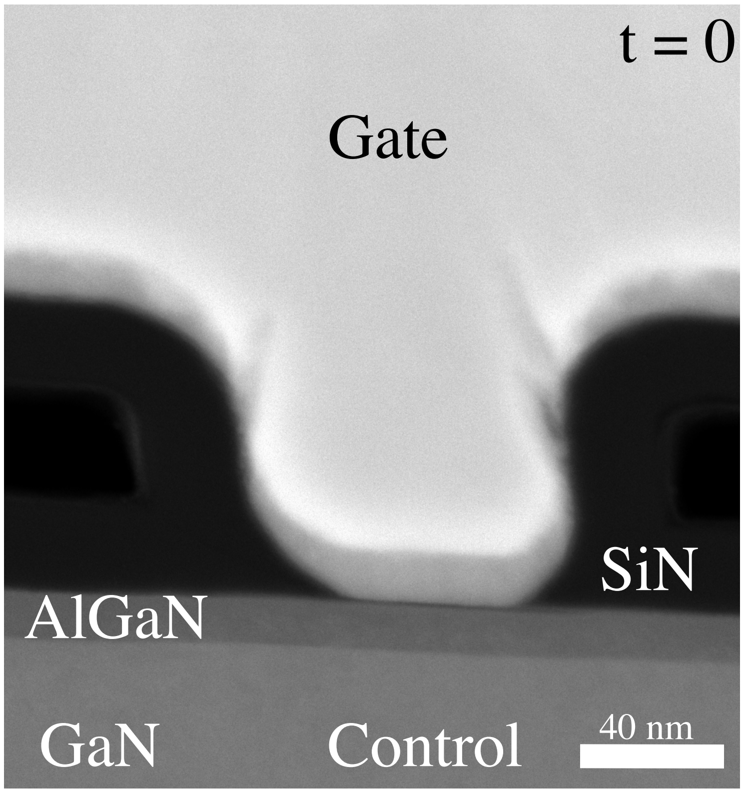


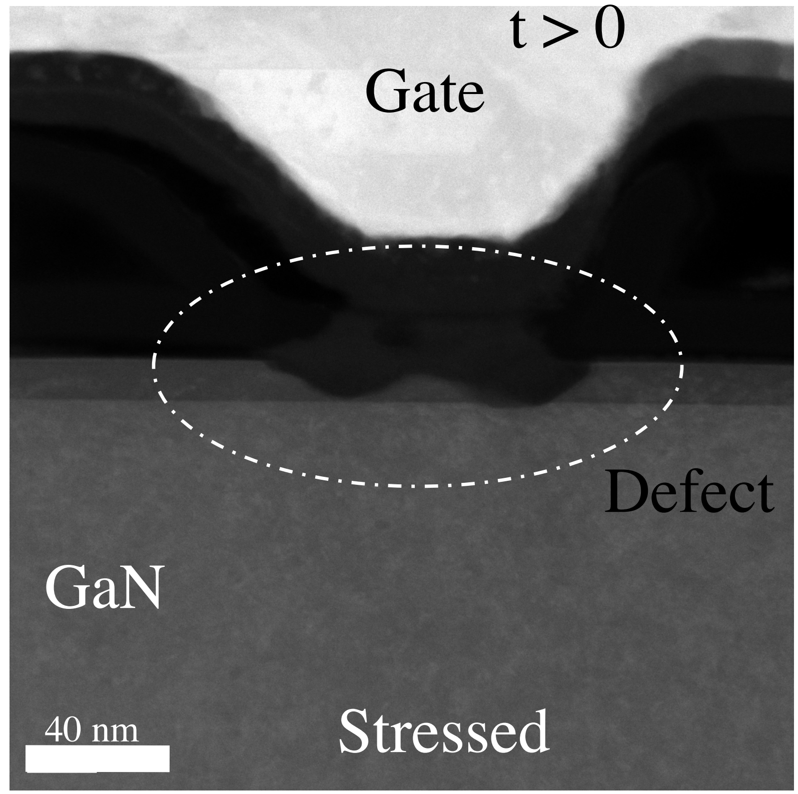
  - TEM analysis by: Dr. Jones's Group

AFRL Device 1813

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate

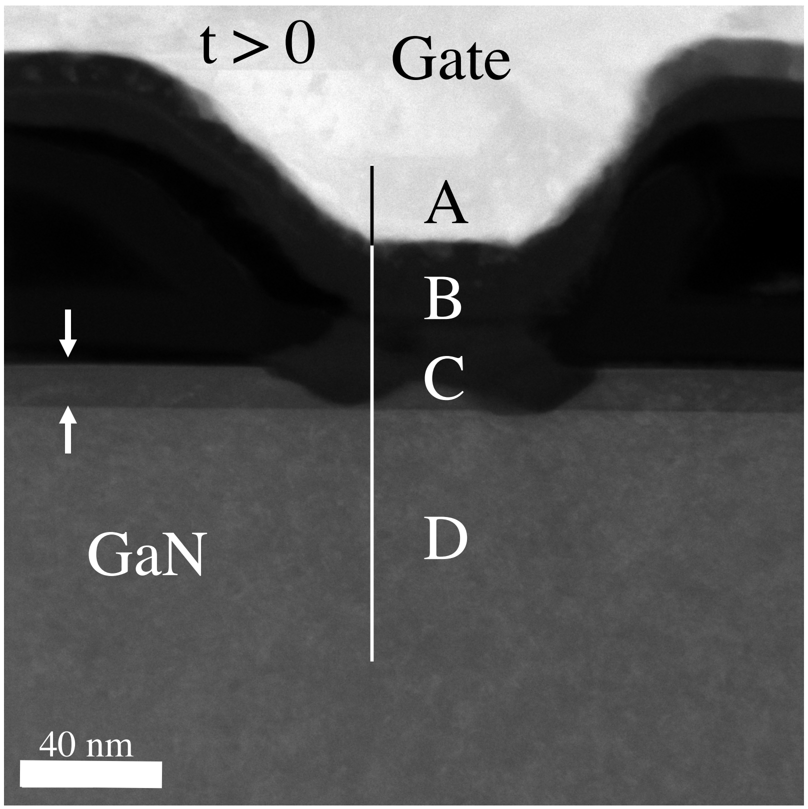
Stress Conditions
V_{DS} = 10V
V_G = -10V to -42V
•1 min steps

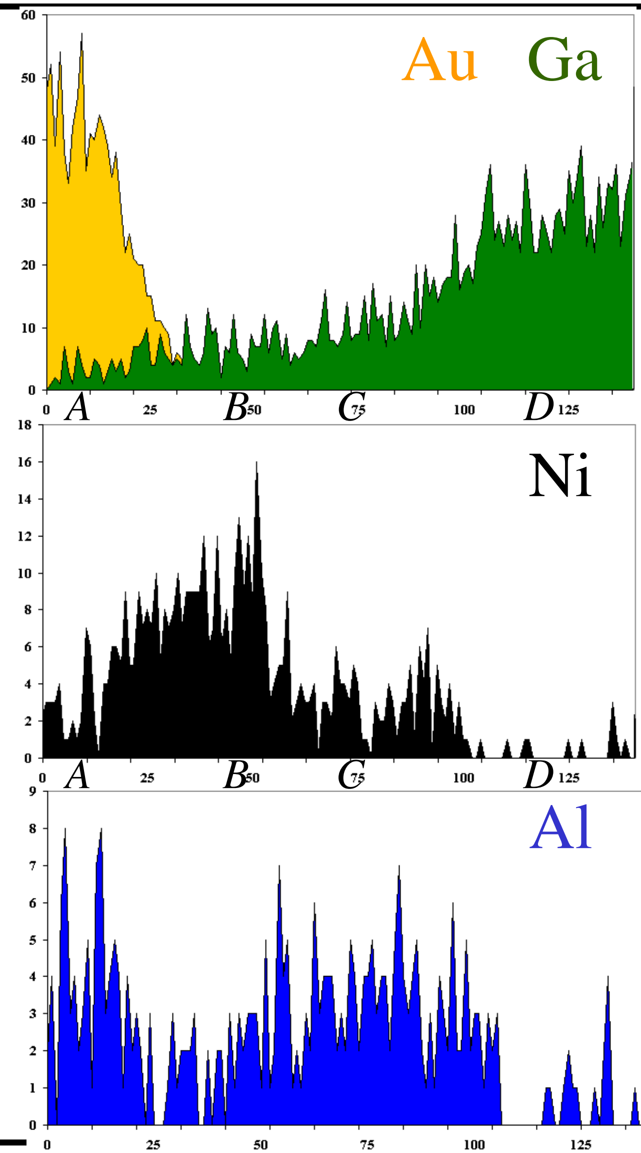




EDS Vertical Line Scan through Defect of 1813

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate

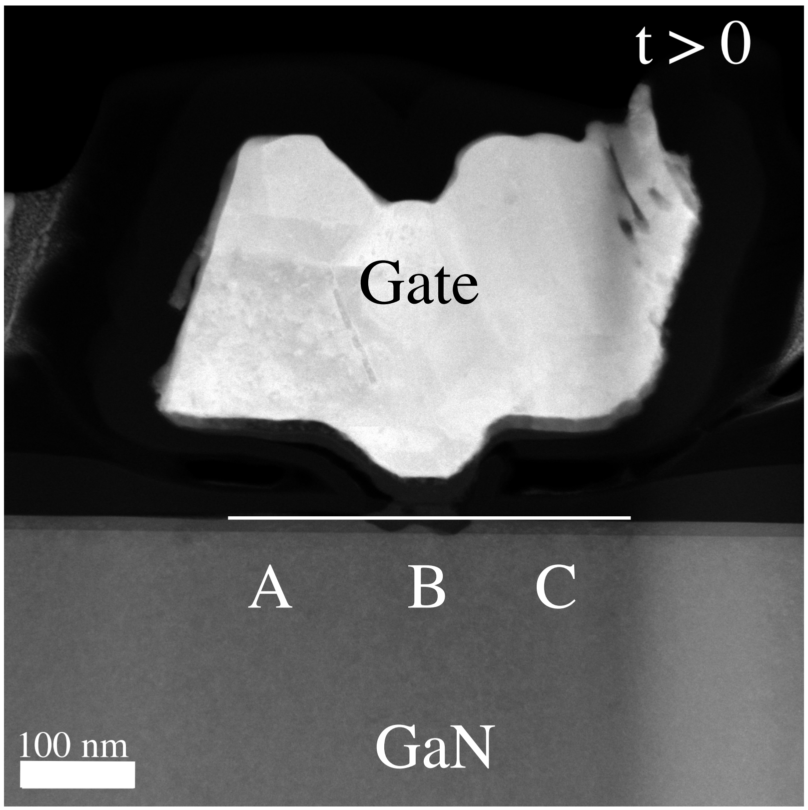


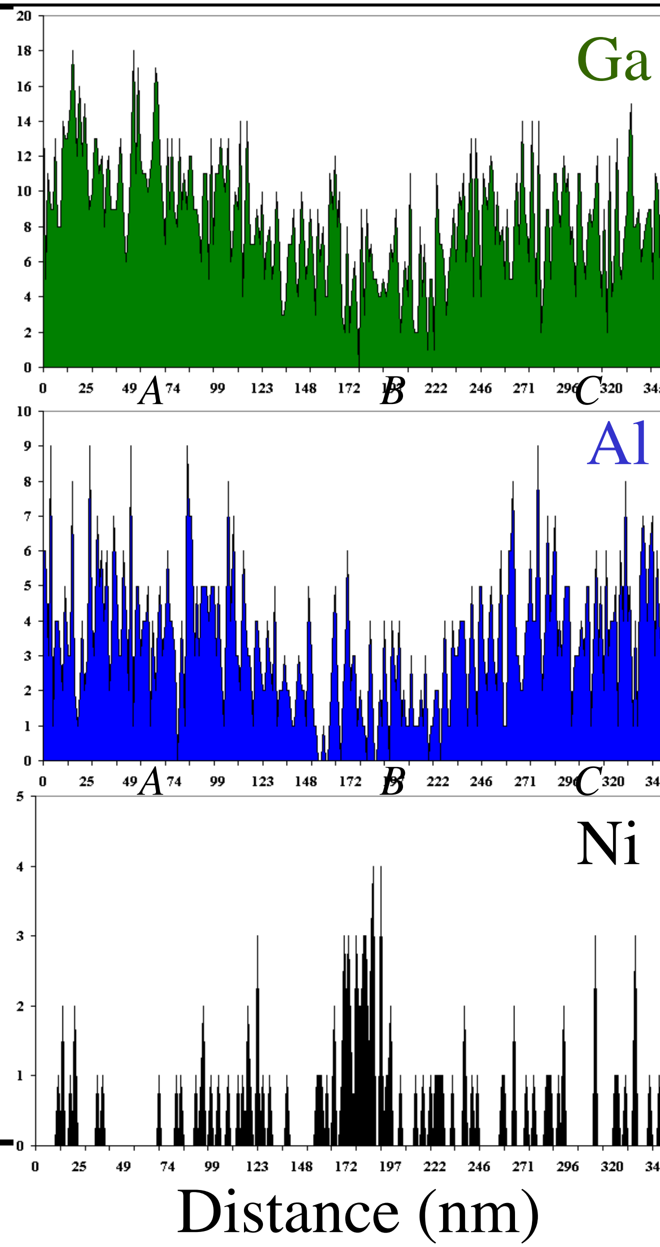


- Increase in Au and Ga in original gate region
- Increase in Ni in AlGaN
- Increase in Al in original gate region

EDS Line Scan across AlGaN Layer of 1813

- TEM (STEM-HAADF)
  - 100nm L_G
  - Ni-gate





•Decrease in Ga

•Decrease in Al

•Increase in Ni

1813 Conclusions

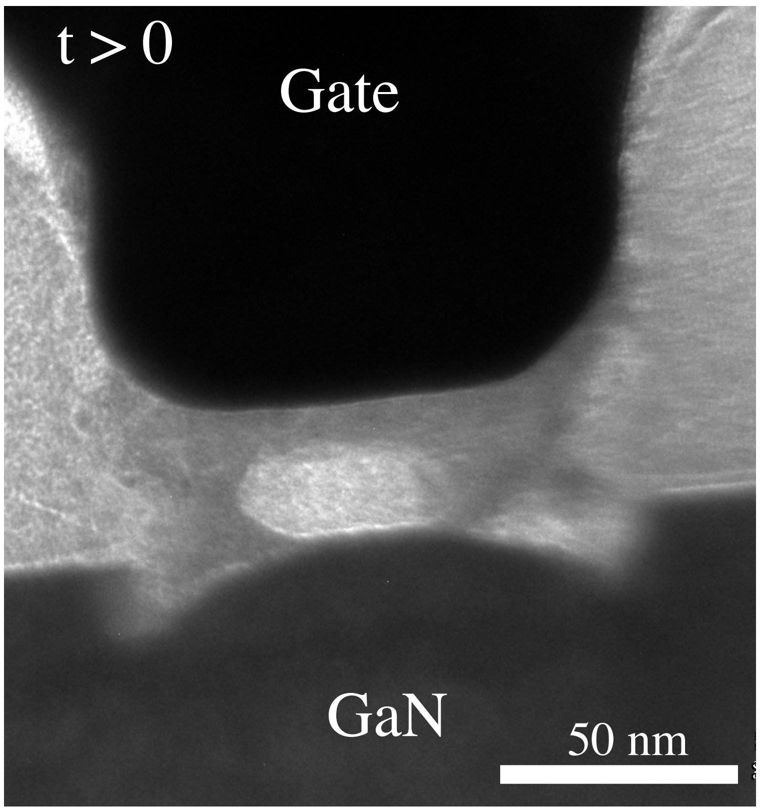
- Larger defect found completely under 100nm gate
- Not prevalent throughout gate width
  - Found only within 25 microns of an edge
  - Approximately 10 slices
- Defect appears to have different compositions in the Nickel gate region and the AlGaN region
  - AlGaN: Increase in Ni
    Decrease in Ga and Al
  - Ni: Increase in Au,Ga, and Al

Defect Comparison

- Two defects observed under high reverse gate bias conditions:
  - TEM

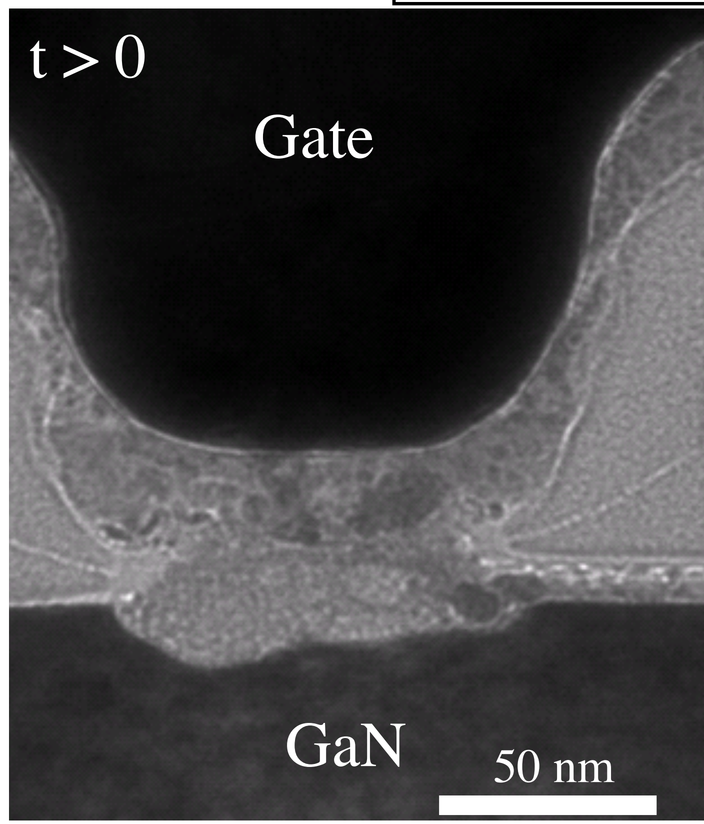
Stress Conditions
V_{DS} = 5V
V_G = -5V to -42V
•1 min steps

- 1514



- 1813

Stress Conditions
V_{DS} = 10V
V_G = -10V to -42V
•1 min steps



Defect Comparison

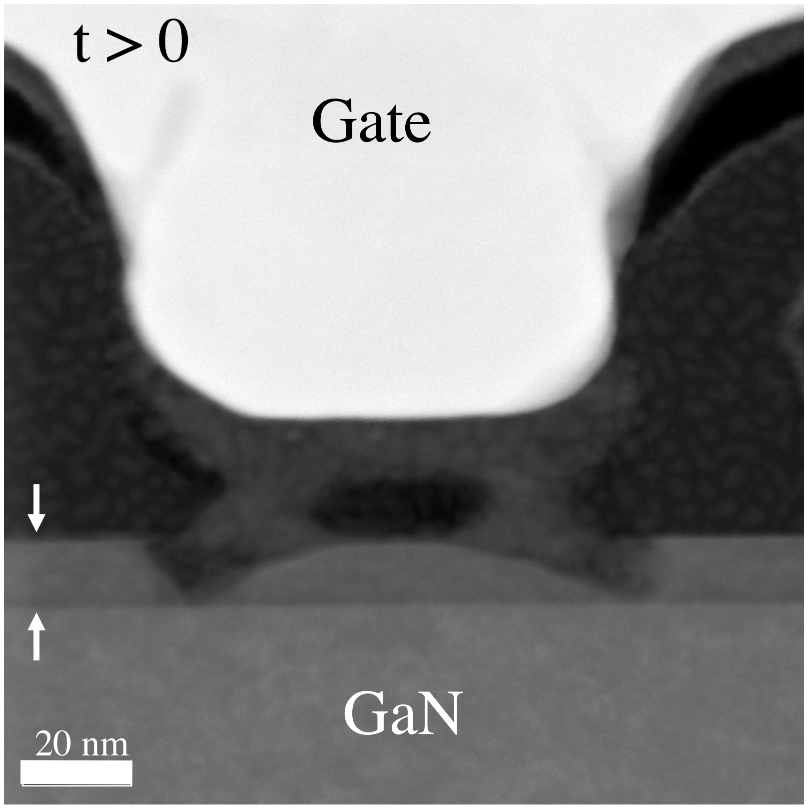
- Two defects observed under high reverse gate bias conditions:

Stress Conditions
V_{DS} = 5V
V_G = -5V to -42V
•1 min steps

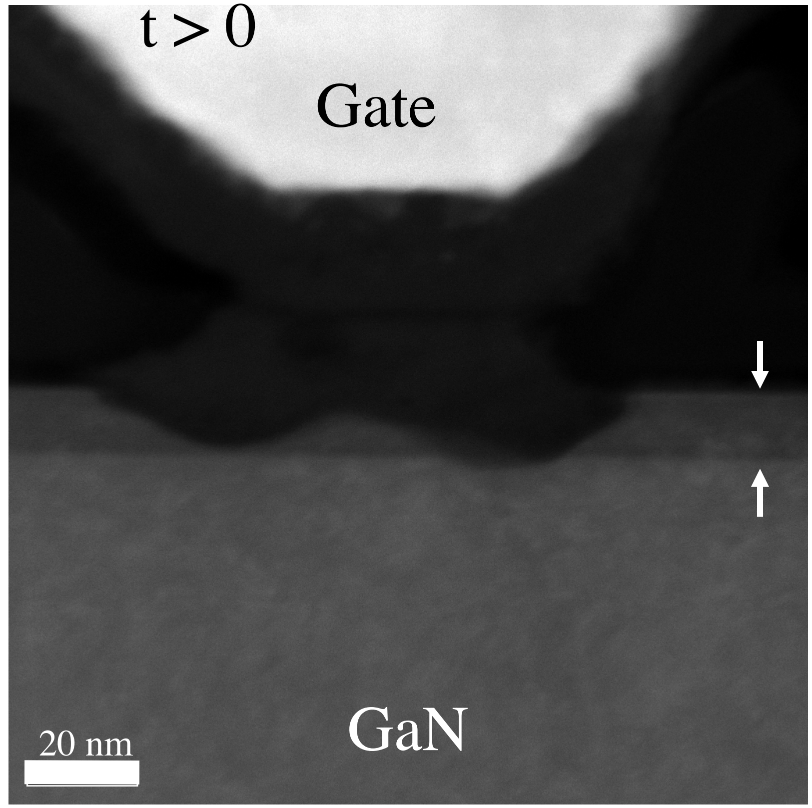
- TEM (STEM-HAADF)

Stress Conditions
V_{DS} = 10V
V_G = -10V to -42V
•1 min steps

- 1514

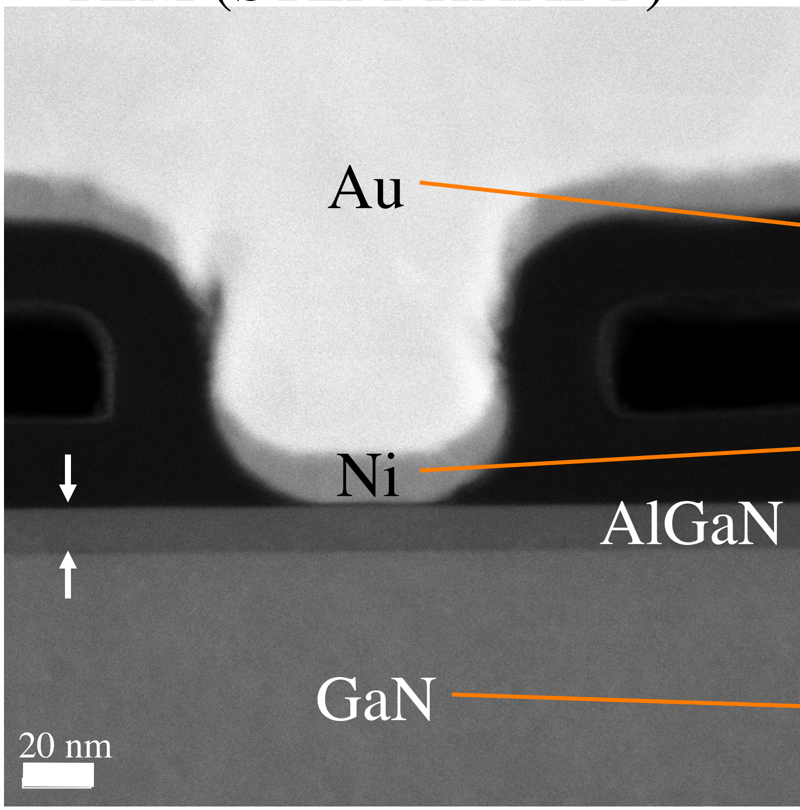


- 1813



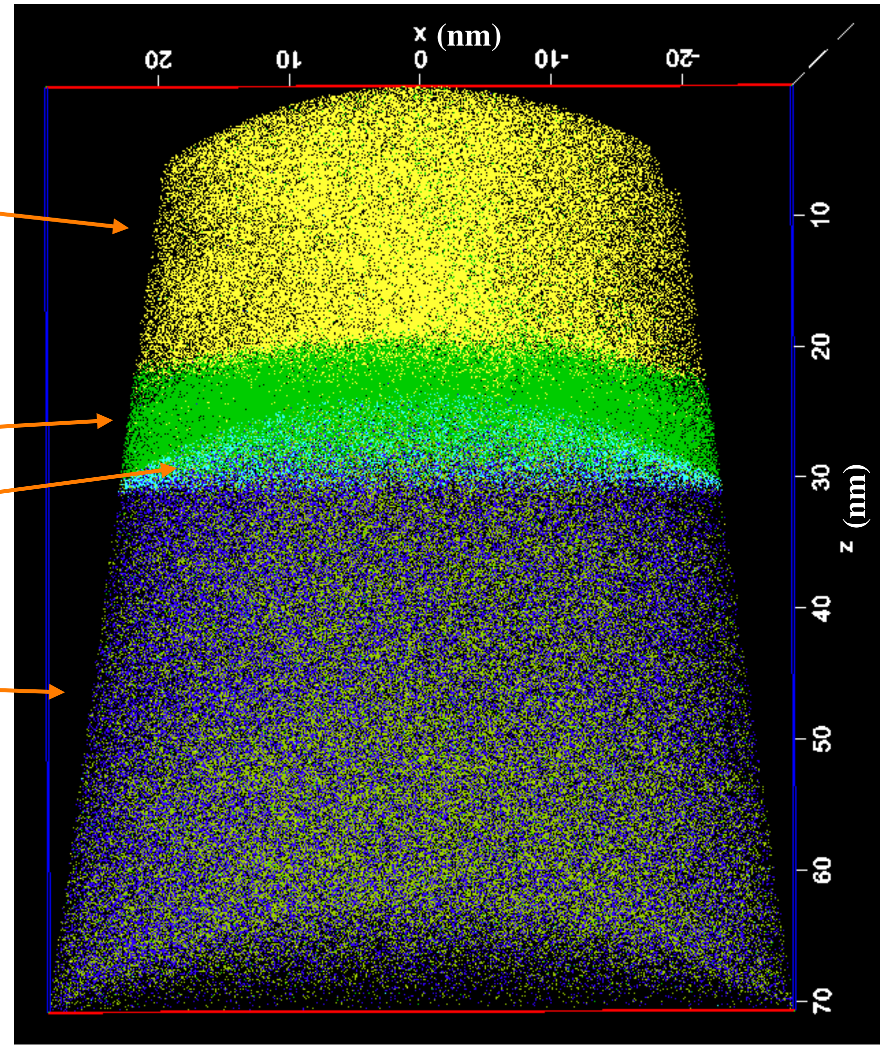
LEAP of AFRL Devices

- TEM (STEM-HAADF)



- Reconstruction flawed due to tip fracture/delamination
- Ni and AlGaN layers are thin and interfaces have poor shape

- LEAP



Outline

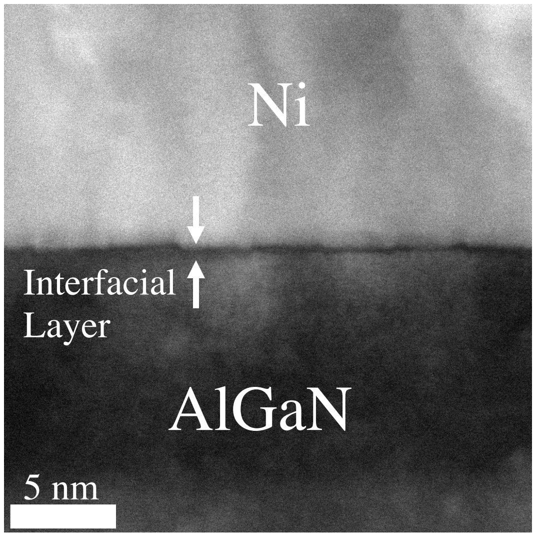
- Devices Analyzed
  - Nitronex (Ni-gate) (t = 0)
    - TEM
      - Interfaces
    - LEAP
      - Review
      - Data Reanalysis → Improved Results
  - MIT (TriQuint) (Pt-gate) (t > 0)
    - Update on Collaboration
    - TEM
      - Interfaces and Defects
    - LEAP
      - Angled tip and results
  - AFRL (Ni-gate) (t = 0 and t > 0)
    - TEM
      - Interfacial defects
    - LEAP
- Limitations of LEAP
- Current Collaborations
- Conclusions
- Future Work

Limitation of LEAP

- Fracturing during LEAP of TriQuint and AFRL HEMTs occurs near interfaces
- Why?
  - Weak interfaces
  - Interfacial layer thickness
  - Pulsing causes stress
    - Delamination
    - Fracture
- But LEAP was successful for Nitronex devices but neither AFRL nor TriQuint?

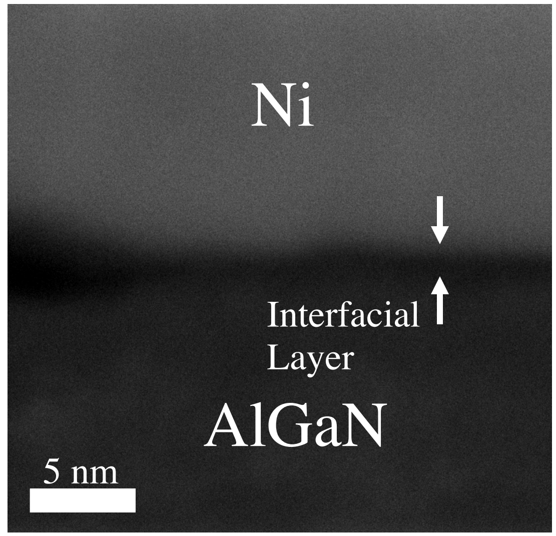
Structural difference between Nitronex, AFRL, and MIT?

Nitronex



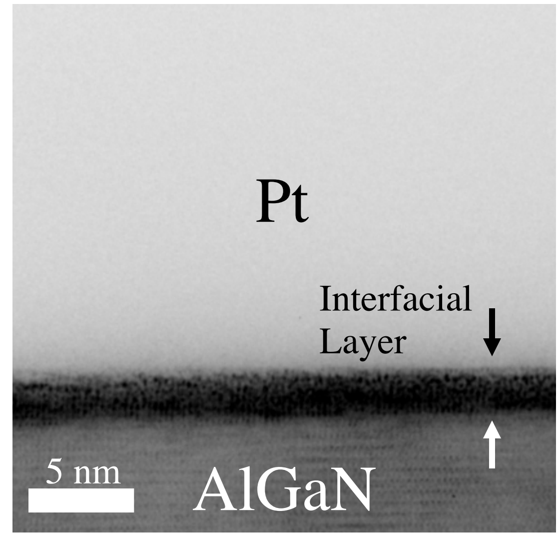
~5 Å

AFRL



~15 Å

MIT



~18 Å

- Nitronex HEMTs have a smaller interfacial layer
  - Only samples that did not fracture or delaminate during LEAP analysis

How to Resolve this Issue?

- Change atom probe systems
  - University of Alabama LEAP limited to laser wavelength of 532 nm
  - Newer systems have wavelengths < 360 nm

- Why is the smaller wavelength important?
  - Larger energy

- Mechanisms for improved evaporation
  - Material with band gaps below laser photon energy
    - Direct excitation
  - Material with band gaps above laser photon energy
    - Creation of holes at tip apex from defects/surfaces/edges
      - Improves tip conductivity, enhances evaporation
    - Thermal excitation

- Who do we plan on collaborating with?
  - University of Tsukuba
  - PNNL

New Atom Probe Collaboration

- Dr. Kazuhiro Hono
  - MMU (Magnetic Materials Unit) formerly NIMS
  - University of Tsukuba (Tsukuba, Japan)

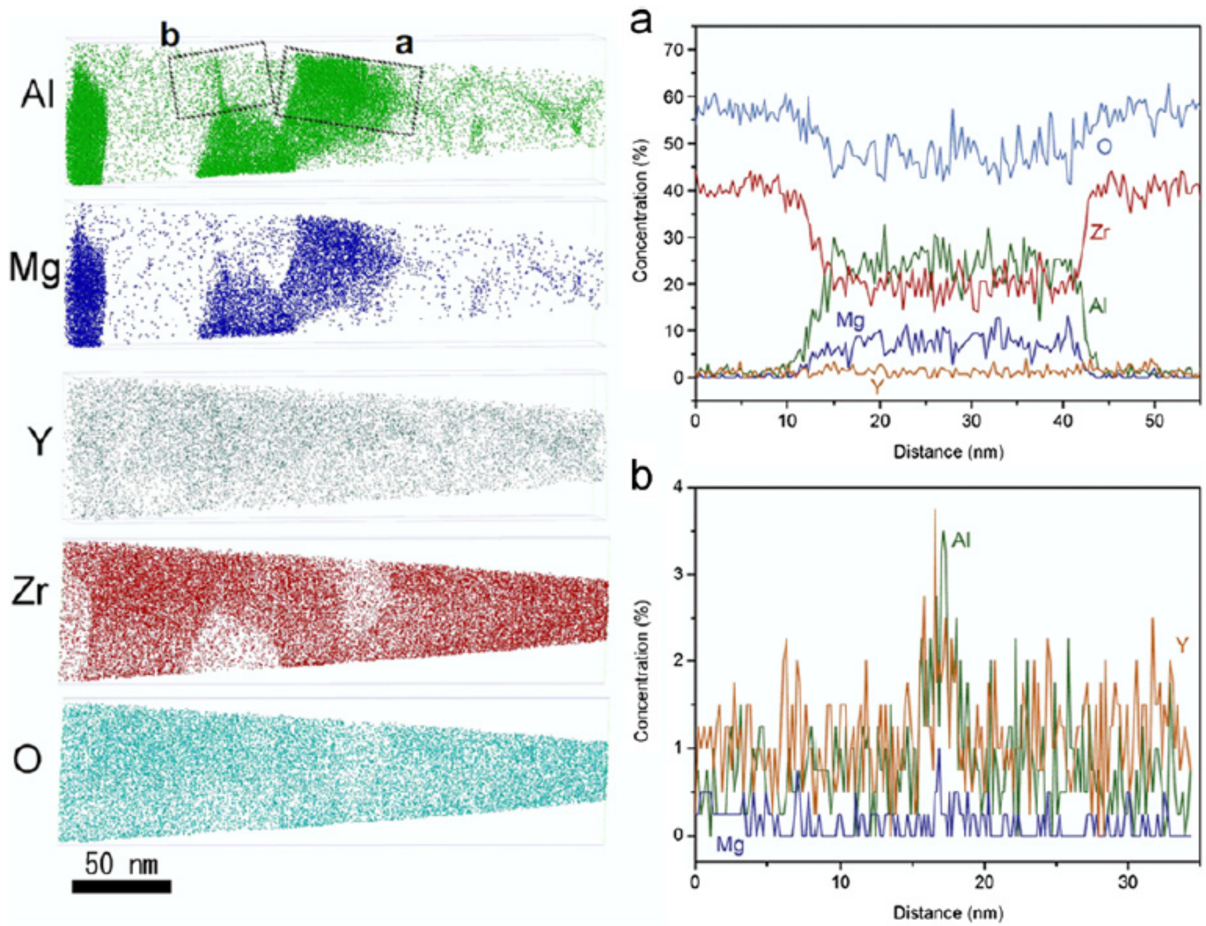
- Custom built atom probe
  - Four available laser wavelengths
    - 1030 nm, 515 nm, 343 nm, 258 nm
      - LEAP only has one wavelength = 532 nm
  - Shown great results working with insulating and wide band gap materials
    - ZnO, MgO, Li(Co, Ni, Mg, Al)O_2 (Li-ion battery)

- Received internship to travel there this summer to complete work
- Started this collaboration in February and were preparing first samples in March but delays occurred (Earthquake/Tsunami)

New Atom Probe Collaboration

- Some of their results on YSZ

K. Hono, *et al*., Ultramicroscopy (2010),
doi:10.1016/j.ultramic.2010.11.020



Atom probe tomography of Al, Mg, Y, Zr and O and concentration profiles calculated from inset boxes (a) and (b)

Another Possible Atom Probe Collaboration

- PNNL (Pacific Northwest National Laboratory)
  - Dr. Theva Thevuthasan
    - Environmental Molecular Sciences Laboratory
  - Shown interest in collaborating
  - Submitting proposal to use facility

- LEAP 4000 XHR
  - Laser wavelength of 355 nm
  - Can use same sample preparation techniques we've been using

Summary

- Studied three different HEMT structures

	Nitronex	MIT	AFRL
Condition:	t = 0	t > 0	t = 0 and t > 0
Analysis:	TEM LEAP -Identified interfacial layer	TEM -pits LEAP -Unsuccessful	TEM -interfacial defects LEAP -Unsuccessful

- Identified three defects in AFRL devices

Not Visible/Found		1514A	1813A
2016A 2112A 0827C/D 1513A	**Stress Conditions** V_{DS} = 0, 0, 5, 15V V_G = -10V to -42V Except 0827 to -50V •1 min steps	**Stress Conditions** V_{DS} = 5V V_G = -5V to -42V •1 min steps	**Stress Conditions** V_{DS} = 10V V_G = -10V to -42V •1 min steps
		•Defect along entire device	•Defect along 20% device

Conclusions

- Improved LEAP analysis by incorporating orthogonal data pipes using iso-surfaces to increase interface resolution
- Begun to chemically identify interfacial defects in AFRL devices
  - AlGaN decreases in Al and Ga

    increases in Ni and sometimes O
  - Al and Ga appear in the defect where Ni part of the gate was located originally
  - Modification of the Ni
- Identified limitations of LEAP for HEMT devices
  - Current laser wavelength is a limitation
  - Establishing collaborations to use systems with smaller λ' s

Future Work

- EDS of AFRL interfacial defects
  - New analytical pole piece should improve detection
- EELS of AFRL interfacial defects
  - Determine N composition
  - Help determine O composition
  - In discussion with FEI on collaboration with newest TEM
- Atom Probe of AFRL devices
  - Structure and composition of defects
- Correlate chemical structure with physical defects
  - Understand formation mechanisms
- Correlate electrical signals for each defect